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COPPER-NICKEL SULPHIDE ORES OF THE NORIL'SK DEPOSITS

BY A.D. GENKIN, ET AL.

A TRANSLATION OF
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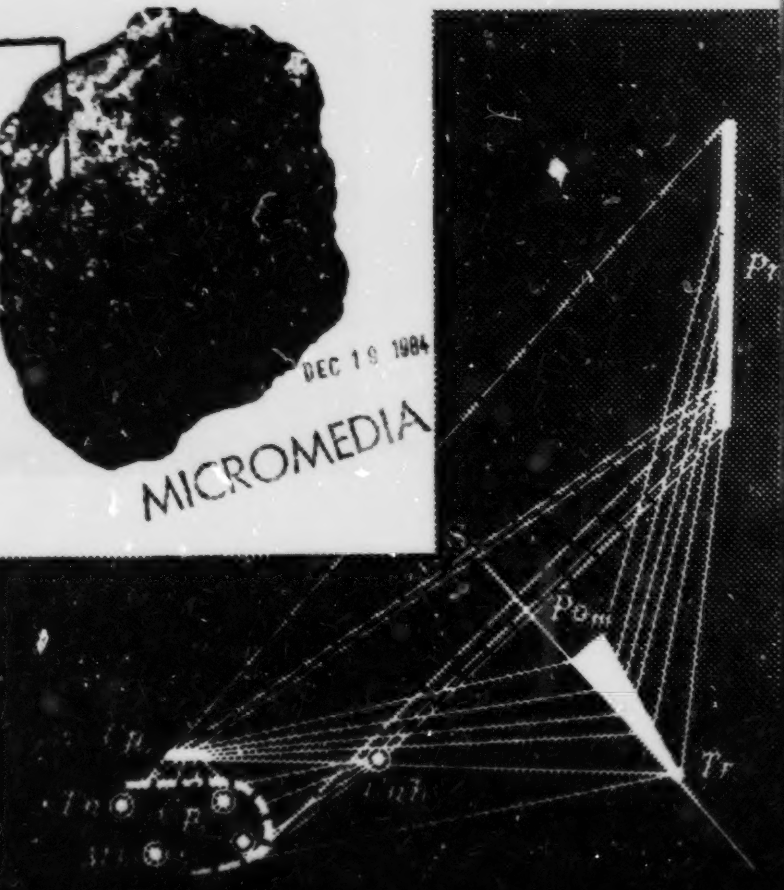

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With best wishes and kind regards
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SUL'FIDNYE MEDNO-NIKELEVYE RUDY NORIL'SKIKH MESTOROZHDENII //
// COPPER-NICKEL SULPHIDE ORES FROM THE NORIL'SK DEPOSITS

In this monograph the copper-nickel sulphide ores from deposits of the Noril'sk region are described; the most recent data pertaining to the geological structure of the deposits and to the petrology of the ore-bearing intrusions are presented; the types of the copper-nickel ores and their mineralogy and distribution in the ore fields and deposits are analyzed in detail; a large number of new minerals is described; the paragenetic associations of minerals and the patterns of their distribution accounting for the zonal structure of the ore occurrences are identified; problems related to the genesis of copper-nickel sulphide ores, such as the behaviour of sulphides in the process of differentiation of sulphide-silicate magmas and the conditions of crystallization of sulphide melts, are also examined.

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FOREWORD

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The major copper-nickel deposits of the world are associated with two metallogenic epochs in the history of the Earth: the Precambrian and the Early Mesozoic. The deposits are distributed very unevenly between the epochs of ore emplacement. Their largest number is confined to the Precambrian nickel-bearing provinces of the Canadian shield (Sudbury and Thompson), the Baltic shield (Monchegorsk, Pechenga and Allarechenskii** ore fields etc.) and the Australian platform (Kambalda etc.). The Mesozoic copper-nickel provinces are much less extensive and the Noril'sk province is the only large one among them.

The deposits of different age have many features in common with regard to their structure and to the sequence of the processes which led to the formation of large mineral concentrations. However, in the Precambrian deposits, magmatic rocks and ores have undergone large-scale metamorphic alterations, making it difficult to study the early stages of ore formation at these deposits and the relationship between the processes of magmatism and mineralization. It is therefore highly important to study deposits from the young copper-nickel provinces, where metamorphic processes are developed on a very limited or negligibly small scale.

Analysis of the current state of the studies pertaining to copper-nickel deposits shows that, in spite of the lengthy history of research on them, the interest in these deposits has not weakened and that publications dealing with these deposits appear in progressively greater numbers both in the Soviet Union and abroad. This is due not only to the great economic importance of the deposits in question, but also to the complexity of the geological processes which led to their formation, and to the multitude of the forms in which the ores are found.

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* Figures in the right-hand margin indicate the page numbers of the original. Translator.

** Transliteration. Translator.

In the world literature there are large comprehensive works dealing with copper-nickel deposits, their geological position, the relationship between mineralization and magmatism, and the mineral composition of the ores. Works of this kind include the monographic descriptions of the deposits at Sudbury by J. Hawley, of the deposits from the Pechenga ore field by G.I. Gorbunov, of the deposits in Finland by H. Papunen, and a number of others.

The main ideas regarding the geology and conditions of formation of the Early Mesozoic deposits from the Noril'sk province are outlined in the works by V.K. Kotul'skii, N.N. Urvantsev and M.N. Godlevskii. However, in spite of the large number of publications dealing with various aspects of the geology, petrology and mineralogy of these deposits, there is no comprehensive work focusing on sulphide ores from the region of Noril'sk. The vast store of evidence accumulated in the course of ten years of study of the Noril'sk deposits prompted the authors to undertake a work of that kind.

In the process of their research, the authors employed a great variety of methods to analyze the composition and properties of the mineral material. Prior to analytical determinations, extensive work was done to develop special techniques of analysis, for calculation of the constant and for determination of the composition of the mineral phases. The composition of different minerals from the Noril'sk deposits was determined by X-ray microanalysis with the help of the microprobe MS-46 "Kameka"* by I.P. Laputina, N.V. Troneva, G.N. Muravitskaya and V.S. Malov, analysts. A number of analyses were done in laboratories of other organizations. All the X-ray studies were performed by T.L. Evstigneeva, G.V. Basova and T.A. Smirnova. Optic studies of the minerals were carried out by L.N. Vyal'sov. A number of the analyses to determine the composition of the rocks and identify individual elements were performed at the TsKhL IGEM AN SSSR*. p.4

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* Transliteration. Translator.

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The authors of the main chapters of this monograph are as follows: chapter I - V.V. Distler and T.L. Grokhovskaya; chapter II - A.D. Genkin, T.L. Evstigneeva, A.A. Filomonova, V.A. Kovalenker and I.P. Laputina; chapter III - A.A. Filimonova, A.V. Smirnov and V.A. Kovalenker; and chapter IV - V.V. Distler, A.D. Genkin and G.D. Gladyshev.

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* TsKhL IGEM AN SSSR = Central Chemical Laboratory of the Institute of Geology and Mineralogy of the USSR Academy of Sciences. Translator.

List of abbreviations of the names of minerals:

Augite (Av)
Actinolite (Ak)
Albite (Ab)
Anhydrite (Ang)
Anorthite (An)
Apatite (Ap)
Apophyllite (Af)
Biotite (Bi)
Brucite (Br)
Valleriite (Val)
Vesuvianite (vesuvian) (Vz)
Wollastonite (Wol)
Galena (Galenite) (Ga)
Hercynite (Hz)
Hypersthene (Hip)
Garnet (Gr)
Datolite (Dt)
Djerfisherite (Df)
Diopside (Di)
Calcite (Cal)
Quartz (Q)
Clinopyroxene (KPX)

Cordierite (Cord)
Xonotlite (Ks)
Cubanite (Cub)
Magnetite (Mt)
Micropegmatite (Mk)
Millerite (Mil)
Mellilite (melilite) (Ml)
Mooihoekite (mooihoeckite) (Mh)
Monticellite (Mnt)
Muscovite (Mi)
Olivine (Ol)
Orthoclase (Ort)
Orthopyroxene (Opx)
Pentlandite (Pn)
Plagioclase (Pl)
Pyrite (Py)
Pyrrhotite (Po)
Pyrrhotite hexagonal (Po_h)
Pyrrhotite monoclinic (Po_m)
Hornblende (Ro)
Rutile (Rt)
Serpentine (Sep)

Sillimanite (Sil)
Sphalerite (Sf)
Talnakhite (talnachite) (Tn)
Thaumasite (Tms)
Tremolite (Trem)
Troilite (Tr)
Fassaite (Fas)
Fayalite (Fa)
Phlogopite (Ph)
Fluorite (Fl)
Forsterite (Fo)
Chalcopyrite tetragonal (Cp)
Chalcopyrite ferruginous (Cp_{Fe})
Chalcopyrite cubic (Cp_c)
Chlorite (Ch)
Zeolite (Ct)
Spinal (Sp)
Epidote (Ep)

INTRODUCTION

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The Lower Mesozoic deposits of the Noril'sk region are confined to the northern extremity of the Siberian platform and form part of a highly specific area known in the literature as the North Siberian nickeliferous metallogenic province [146]. In this province a number of deposits and concentrations of copper-nickel sulphide ores associated with trap intrusions have been established. In contrast to the rest of the platform, the northern part of the Siberian trap region is the site of volcano-plutonic complexes, among which, in addition to normal traps, there also occur more markedly basic magmatic rocks, which may have formed at greater depths. Rocks with higher basicity levels are found among the effusive (extrusive) and intrusive trap facies. Among the extrusive rocks these varieties are represented by olivine tholeiites and picrite basalts. Among the intrusive trap facies highly characteristic layered rock massifs with facies horizons of ultrabasic rocks have been recorded.

The coexistence of intrusive and extrusive rocks having increased levels of basicity, with copper-nickel sulphide ores appears to be one of the most important features of the copper-nickel provinces. A rock association of this type has been encountered within the boundaries of the Kola region in the Proterozoic structure of the Pechenga synclinorium, to which the main copper-nickel deposits are confined. The volcano-plutonic complexes of this region may be also regarded as ancient trap formations. As a result of the studies carried out in recent years it has been established that ultrabasic extrusive rocks are relatively widely distributed in a number of different provinces of the world [249]. A close association of copper-nickel sulphide ores with these rocks has been recorded in deposits in Western Australia and in a number of other provinces of the world [249,254]. The regularity with which sulphide ores associate with this type of magmatic formations, appears to be due to the specific structure of the upper (outer) mantle, the conditions of fusion and the position of magma chambers therein. Geophysical data on the northern part of the Siberian platform suggest that the upper boundary of the mantle is somewhat raised. If this is the case, regional tectonic structures may expose there deeper parts of the zones of magma formation in the mantle, even though they may have originated at the same depth as analogous structures from other parts of the platform [44]. Furthermore, the region may owe its specific metallogenic aspect not only to the vertical, but also to the lateral non-uniformity of the mantle [11]. In the model of fusion of the upper mantle [54] the sequential formation of relatively low-temperature and higher-temperature melts appears to be the main factor responsible for the coexistence of compositionally different rocks in genetically integral complexes of basic rocks. These complexes may include essentially silicate rocks, as well as sulphide-silicate magmatic products. The two types of rocks should differ, however, not only in their contents of sulphides, but also with respect to the composition of the silicate melt itself. Indeed, within the boundaries of the region examined the largest concentrations of sulphides are associated with layered intrusions which differ in composition from other trap intrusions. The process of formation of copper-nickel sulphide ores is one of the stages in the general developmental cycle of trap magmatism. This is evident not only from the localization of their deposits in the zones with definite volcano-plutonic assemblages and from the association of mineral concentrations with corresponding types of magmatic rocks, but also from the unity of the geological and tectonic factors controlling the distribution of magmatic rocks and copper-nickel ores. Sulphide mineral concentrations, together with intrusive rocks, form ore-magmatic systems, in which mineralization is part of the general process of magma formation, differentiation and crystallization of sulphide-silicate magmas.

In order to understand more fully the laws governing the formation and distribution of copper-nickel deposits it is imperative that further detailed studies be carried out, primarily in the area of the conditions under which sulphide ores form. These studies should include research into the problems of petrology of the ore-bearing magmatic complexes and of the relationship between the sulphide and silicate mineral associations during the crystallization of basic magmas, a detailed mineralogical analysis of the ores and an analysis of the zoning and relationship of the ores with magmatic and metamorphic rocks. Our work deals in greater or lesser detail with many of these problems.

CHAPTER 1 p.7

Geological structure of copper-nickel sulphide ore deposits

A brief outline of the geological structure of the Noril'sk region

The Noril'sk region is the most important area of distribution of copper-nickel deposits in the north of the Siberian platform. The Noril'sk, Talnakh and Oktyabr'skii* deposits, as well as a number of smaller ore deposits and mineral concentrations (fig. 1) have been established within its confines.

In examining the main patterns of distribution and formation of the deposits throughout the geological history of that province it is convenient to differentiate its evolution into the pre-trap, trap and post-trap stages. The pre-trap stage comprises the formation of the regional metamorphic and sedimentary complexes of the Proterozoic and Middle Paleozoic age composing the lower and middle structural levels of the platform mantle; the trap stage corresponds to the time of formation of the thick basaltic extrusive-explosive group (series) of rocks composing the upper structural level of the region, and of the Upper Paleozoic-Lower Mesozoic trap intrusions conjugated with it. The post-trap stage encompasses the formation of the Jurassic-Cretaceous sedimentary rocks having a limited distribution, and of the Mesozoic granitoid massifs.

The structure of the platform basement in the Noril'sk region is inaccessible to direct observation. Limited information has been obtained by analyzing the composition of the fragments encountered in eruptive rocks of some of the volcanic structures [112]. Results of the analyses evidence the presence of Precambrian schists, gneisses, granite gneisses and granites in the composition of the basement.

The pre-trap complex of rocks comprises predominantly deposits of the grey and variegated terrigenous-carbonate formations. The main lithological varieties of the lower, Cambrian-Ordovician part of the section are represented by dolomites, argillaceous or calcareous dolomites, less often by limestones or marls. The content of terrigenous material increases in the Silurian rocks, where the bottom part of the section is composed of argillites and siltstones.

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* Transliteration.Translator.

Younger deposits of the Late Silurian-Early Devonian age include rocks of the terrigenous-carbonate-gypsiferous formations. The leading lithological varieties are here limestones, calcareous marls, dolomites and dolomitic marls, gypsums and anhydrites. The same assemblage of rocks, but with a different proportion of terrigenous material, occurs in the Upper Devonian and Lower Carboniferous section. Argillites and calcareous argillites with interlayers of sandstones, phosphorites and marls compose the lower part of the Middle-Devonian section. The upper part of the Middle and Upper Devonian is represented mainly by sulphate-carbonate, argillaceous carbonate and, to a lesser degree, silicate-carbonate sediments. Calcareous and dolomitic marls, gypsums, anhydrites, limestones and dolomites predominate among them. There have also been encountered horizons of salt.

In spite of the fairly varied lithology of the rocks composing the pre-trap complex, it is evident that the pattern of structural evolution in the Noril'sk region was essentially the same throughout the Lower and Middle Paleozoic. The most substantial changes appear to correspond in time to the accumulation of the Late Devonian-Early Carboniferous sediments. p.8
The orientation of the principal structural-formational** zones alters from submeridional to northeastern. Formation of the major structures in the region of the Khantaiskii*-Rybninskii* anticline having a northeastern trend, and of the Noril'sk-Kharaelakhskii* and Lama-Khantaiskii troughs bounding that anticline, is confined to that time.

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* Transliteration. Translator.

** The term "structural-formational zone" was introduced in 1944 by Nikolaev, who also provided in that work descriptions of different types of such zones. Translator.

The Lower-Middle Carboniferous boundary is characterized by a general uplift of the territory and by a change to continental conditions of development. Deposits of the Upper Paleozoic are represented by a terrigenous-carbonaceous formation, where the main lithological varieties are sandstones, siltstones, argillites, coals, cemented gravel and conglomerates. The beds of these sediments as a whole have a rhythmic structure [50]. From the tectonic viewpoint the deposits of the upper structural stage mirror the structural plan of the earlier epochs, since the consedimentary development of the Rybninskii anticline continues, and the troughs bounding that anticline contrast with it more and more sharply. The inception of the flexures conjugating the anticline to the adjacent troughs, is an important moment in the development of the general structural framework of the region. The flexures appear to reflect the large-scale fractures that appeared in the basement during the Middle and Upper Paleozoic [109]. The trap complex of rocks completes the formation of the upper structural stage in the platform mantle and is localized in the zone of the troughs bounding the Khantaiskii-Rybninskii elevation (see fig. 1). The beginning of the volcanic activity appears to coincide in time with formation of the terrigenous complex of rocks of the C_3-P_2 age (the Tunguska group), but the most active phase of volcanism corresponds to the time interval between the Upper Permian and Middle Triassic. Trap deposits totalling 2500m in thickness formed during that time.

The complex of rocks amalgamated into the trap formation comprises explosive-extrusive, subvolcanic and intrusive products that are predominantly basaltoid in composition. Different locales of the trap province from the northern part of the Siberian platform display different features of magmatism depending on the character of their tectonic development. These locales represent in fact blocks, in which, as a result of the interaction of folding and disjunctive movements that were particularly intensive during the Hercynian time, there arose structural conditions suitable for a sequential injection of compositionally diverse magmas [49,144,147]. The distinctive feature of trap magmatism in the Noril'sk region is the presence of subalkaline and ultrabasic derivatives, such as trachybasalts, trachydolerites and picrites [42], alongside normal trap rocks.

In the development of trap volcanism there have been distinguished four tectono-magmatic phases corresponding to the alternating stages of compression and extension of the consolidated platform [42,147]. The main phases are as follows: 1) Late Permian, trachybasaltic; 2) Early Triassic, andesite-basaltic, picrite-basaltic phase; 3) Early Triassic, basaltic; and 4) Early-Middle Triassic, basaltic. The most distinctive feature of magmatism in that region is the cyclicity of lava eruptions and the antidromal sequence of eruption of compositionally different melts in each phase [98,43]. The most pronounced differentiation of volcanic products has been recorded in the Late Permian-Early Triassic phases. The early eruptions of lavas are represented by the most acidic group of subalkaline titanaugite trachybasalts and trachyandesite basalts. With regard to their petrochemical characteristics these rocks are supersaturated tholeiites with standard (normative) quartz and hypersthene. The next age group of rocks from this phase includes andesite basalts, labrador and two-feldspar basalts corresponding to normal tholeiites with standard quartz (no more than a few percent), but without normative olivine. Younger rocks are represented by olivine-plagioporphyry and olivine basalts belonging to the group of p.9 olivine tholeiites. Extrusive picrites complete the formation of the rocks of the early magmatic phase (Table 1).

The sheets of these rocks are among the most characteristic extrusive formations in the Noril'sk province, but on the regional scale their distribution in the North of the platform is not very extensive being practically restricted to that particular territory. The sheets of picrite basalts attain their greatest thickness (up to 150-200m) in the axial part of the zone in which they occur, and gradually decrease in thickness towards the lateral peripheries (flanges) of that zone. In the adjacent territories the analogous parts of the section are composed of olivine and subalkaline basaltoids instead of picrites.

In the subsequent volcanic phases the antidromal sequence of eruptions is less well pronounced. With regard to their composition normal tholeiite and olivine-platiophyre basalts are the extreme varieties of the late volcanic phases in most of the Noril'sk province. As a result of recent studies there have, however, been [66] identified rocks close to picrites among the constituents of later traps in the northern part of the province.

Explosive facies are found in all the phases of trap magmastism, but the late phase has the highest relative content of explosive products.

The post-trap complex of rocks is developed on a very limited scale in the Noril'sk region. The greatest thickness of Jurassic-Cretaceous sediments has been recorded in the troughs bounding the platform. The known magmatic manifestations of the Late Mesozoic age are represented by small stock-like intrusions of granitoids [94] located in the western part of the region. The formation of these granitoids may be related to the processes of activation of the Siberian platform during the Mesozoic.

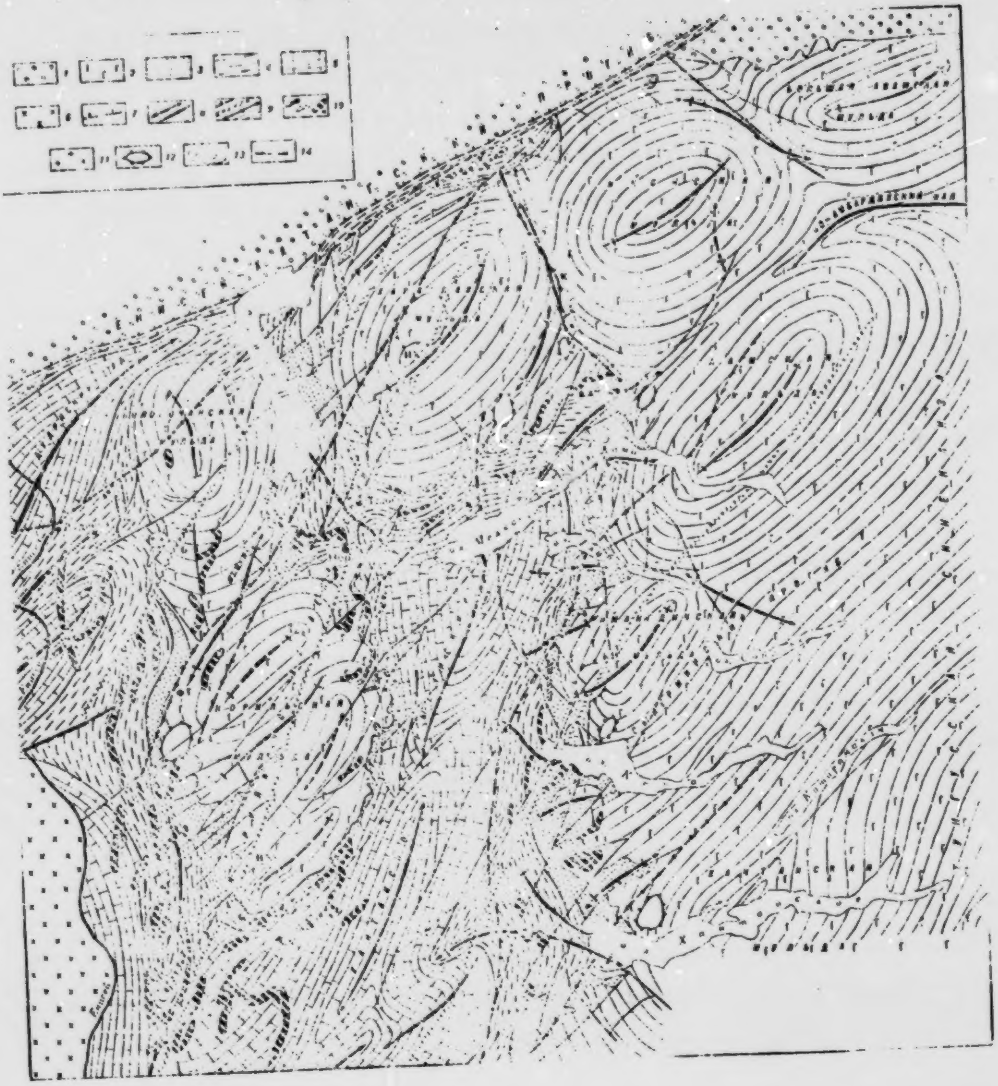
INTRUSIVE TRAPS

General description of intrusive traps

The trap formation in the north of the Siberian platform includes a complex of intrusive products of basaltic magmatism in addition to extrusive rocks.

Intrusive rocks have been recorded throughout the section of the upper and middle stages in the platform mantle, from the Silurian deposits to the Permian-Carboniferous terrigenous sediments. Intrusive rocks concentrate mainly in the marginal zones of trap depressions. In isolated loci intrusive rocks amount to 20-40% or even 60% of the section volume.

Fig. 1



Structural-tectonic map of the Noril'sk region (prepared by L.L. Vaulin and N.F. Shchedrin, 1977).

Structural stages:

1- Middle-Upper Mesozoic (K-I);

2- Lower Mesozoic-Upper Paleozoic (T-P_2iv);

3- Upper Paleozoic (P_2-C_3);

4- Middle Paleozoic (C_2-D);

5- Lower Paleozoic (Vendian) (S-PR_3^3);

6- Upper Proterozoic (Riphean) (PR_3);

7- The boundary of the Enisei-Khatanga trough;

8- Folded structures; a-anticlines; δ-synclines;

9- Disjunctive structures: CX-North Kharaelakhskii; б-Bogandinskii; П-Pyasina; фТ-Fokino-Tangaralekhskii*; Д-Daldykanskii; HX-Noril'sk-Kharaelakhskii; K-Kumginskii*; KC-Kystyktakhskii*; ИЛ-Imandinskii*-Letninskii*; KИ-Keta-Irbinskii*; X-Khantaiskii;

10-Intrusive formations: a-differented intrusions of gabbro-dolerites; δ-weakly differentiated intrusions of gabbro-dolerites;

11-The Bolgokhtokhskii* intrusion of granite (quartz) porphyries;

12-Paleovolcanoes;

13-Isopachytes of tuff lava formations;

14-The zone of maximum thicknesses in the horizon of picrite basalts.

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* Transliteration. Translator.

TABLE 1 Magmatic rocks of the trap formation from the Noril'sk province

Cycles	Subformations of extrusive traps	Suites (sets)	Rocks	Assemblages of intrusive traps	Morphology of the bodies and the rocks
Late Permian	Trachybasaltic	Ergalakhskii*	Tuffs, tuff sandstones, tuff breccias, titan-augite trachybasalts, trachyandesite basalts	Ergalakhskii	Undifferentiated sills, titan-augite dolerites
Early Triassic	Differentiated complex of lavas	Ivakinskii*	Tuff breccias, tuff agglomerates and ash tuffs, andesite basalts, labrador basalts and two-feldspar basalts	Pyasina	Subtabular, ring-shaped or vertical bodies, trachydolerites and trachyandesite porphyries
		Syverminskii*	Tholeiite and olivine-plagioporphyry basalts	Syverminskii	Undifferentiated sills, poikiloophitic gabbro-dolerites
		Gudchikhinskii*	Aleuropsammitic tuffs, picrite basalts	?	-
Early Triassic	Basaltic	Khakanchanskii*	Basaltic tuffs, tuff breccias and tuff lavas	Vetkinskii	Undifferentiated sheets and dikes, porphyroid dolerites
		Tuklonskii*, Nadezhdinskii*	Tuffs, tuff breccias, tholeiite basalts	Onocherskii*, Katanga	Undifferentiated tabular bodies, gabbro-dolerites

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* Transliteration. Translator.

(Table 1 continued)

		Morongovskii*	Aleuropelitic basaltic tuffs, trachybasalts, tholeiite or (less often) picrite basalts	Fokino	Differentiated gently dipping (low angle) cross-cutting bodies, olivine and troctolite gabbro-dolerites
Early-Middle Triassic	**Basaltic**	Mokulaevskii*-Samoedskii*	Alternating aleuropelitic, psammitic and psephitic basaltic tuffs and porphyritic or glomeroporphyritic basalts	Mokulaevskii-Samoedskii	Dikes, porphyroid dolerites
				Daldykanskii	Steeply dipping (high-angle) cross-cutting bodies and dikes, porphyroid olivine gabbro-dolerites
				Avamskii*	Dikes, trachydolerites

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* Transliteration. Translator.

Taken in conjunction, the geological, petrological and structural-tectonic data available suggest that most of the intrusive traps are comagmatic with the corresponding volcanic phases [42] (see Table 1). Intrusions form at the conclusive stages of volcanic phases as a result of plugging of the magma feeders with crystallized melts, as well as in the process of alternation of the tectonic regimes of compression and extension. The trap intrusives are commonly close in composition to the volcanic rocks comagmatic with them, but the extrusive rocks are, as a rule, somewhat more acidic than the intrusive varieties [137]. This is quite logical if we take into account that a characteristic feature of the trap magmas is their antidromal differentiation. Most of the trap intrusions are of the type of sulphide-free undifferentiated massifs (see Table 1). In the Noril'sk region there have been distinguished nine complexes of undifferentiated intrusions. For the most part these are tabular, subconcordant or, less often, cross-cutting dike-like bodies of gabbro-dolerites, dolerites, trachydolerites, titanaugite dolerites and trachyandesite porphyries. There have also been distinguished there two complexes of intrusive rocks closing the process of formation of the trap association. These complexes are high-angle cross-cutting bodies and dikes of porphyroid olivine dolerites and trachydolerites.

Sulphide-bearing differentiated intrusions are considerably less widely distributed intrusive formations. Intrusions have been recorded in different parts of the section of the platform mantle, from the deposits of the Silurian age to the lower horizons of extrusive traps. Most of the differentiated intrusions are localized in sedimentary rocks of the platform mantle. The only known intrusions extending all the way to the bottom part of the section of the differentiated complex of lavas are confined to the Noril'sk trap depression (the Ivakinskii and Syverminskii suites). Nowhere in the Noril'sk province has the roof of the sulphide-bearing intrusions been found to occur above these lava horizons. It is, however, believed that the apophyses p.11
of the flanges of these intrusions do rise into higher horizons

of the tuff lava section. These data are in fact the main evidence on the basis of which the chronological position of the differentiated intrusions is determined. The ambiguous results of the geological observations regarding the relative age of the intrusions account for the existence of two different types of schemes used for differentiating intrusive traps by age.

In the two types of schemes the formation of intrusive traps is differentiated into four and six tectono-magmatic stages, respectively. These schemes differ mainly in their approach to substantiating the comagmatic nature of intrusive and extrusive rocks. The schemes dividing the formation of intrusive traps into four stages are based on the assumption that all the magmatic products are fully comagmatic [147]. The other schemes [42,95 and 109] recognize that some of the trap intrusions, mainly the undifferentiated ones, evolved in association with corresponding phases of volcanism, but refer the formation of the differentiated massifs to the postvolcanic tectono-magmatic stage. Furthermore, there have been identified late (Daldykanskii and Avamskii) complexes of undifferentiated intrusions and dikes concluding the trap magmatism in the north of the Siberian platform [109].

These differences in the approach to the age of the differentiated and undifferentiated intrusions are due to the inadequacy of the direct geological evidence substantiating the relationship of the extrusive and intrusive traps on the one hand and of the trap intrusions within their respective groups on the other. It appears to us highly important that there is a fairly strict correlation between the spatial distribution of differentiated intrusions and the fields of development of the differentiated complex of lavas, including the sheets of ultrabasic rocks represented by picrites. The concurrence of the different types of magmatic formations in space cannot be explained by a mere coincidence of the fields of their development. There is probably a genetic reason for the concurrent development of definite types of extrusive and intrusive rocks. This is borne out by a number of regional and local patterns regularly observed in the development of magmatism in the Siberian platform. For example, it has been established that the basicity level of the lavas steadily increases towards the northwestern part of the platform, and that the relative content of differentiated intrusive rocks increases concomitantly among the intrusive trap products. In the locales marked by the maximum development of ultrabasic lavas, there occur differentiated intrusions with horizons of ultrabasic rocks. The differentiated intrusions of the Noril'sk type known at present are found in locales with the greatest thicknesses of picrite basalt sheets. The characteristic features of magmatism of this kind have evolved to some degree as a result of the tectonic conditions prevalent in the peripheral part of the platform.

The data of deep seismic probing suggest the presence in the Noril'sk province of plutonic tectonic structures involving not only the crustal region, but also the upper mantle. Plutonic regional tectonic structures may extend all the way into deep-seated horizons of the mantle thus providing for the migration of compositionally diverse magmas into the crustal region. The differentiated series of lavas including ultrabasic extrusive rocks, and the differentiated intrusive rocks are therefore related at least by paragenesis, if not genetically.

Absolute geochronological data on trap magmatism show that the injection of intrusive traps encompasses the time-interval of 200-250 million years [75], hence coincides with the general geological age of trap formation from the Late Permian to the Middle Triassic. It is characteristic that most of the figures from the numerous datings of the major differentiated intrusions from the Noril'sk province are in the range of 220-250 million years. These figures generally correspond to the early phases of trap volcanism, since the Permian-Triassic boundary dates back 250 million years. p.12

THE TYPES OF THE SULPHIDE-BEARING INTRUSIONS AND THE MAIN CHARACTERISTICS OF THEIR STRUCTURE

Patterns of distribution and morphology of the intrusions

Detailed studies have been conducted on the differentiated intrusions for a fairly long time, since the initial discovery of ore deposits in the Noril'sk province. The great interest aroused by these highly specific manifestations of trap magmatism is fully justified, since copper-nickel ores are associated only with these magmatic formations. The copper-nickel mineral concentrations are represented by sulphides disseminated within the intrusions, as well as by morphologically diverse ores found in their exocontacts. Large-scale comprehensive research has been carried out under the direction of V.K. Kotul'skii, N.N. Urvantsev and N.M. Godlevskii. There is also a number of works dealing with individual intrusive massifs by N.F. Smirnov [134], I.A. Korovyakov [97], D.A. Dodin [64,65], V.V. Zolotukhin [75,71], L.L. Vaulin and E.N. Sukhanova [8,139] and other researchers. The problems related to petrochemistry of the intrusive traps are examined in detail in the works by A.M. Vilenskii [10].

In addition to the already existing schemes dividing the differentiated massifs into complexes [12] and petrochemical series* [10], it may be suggested that the intrusions be classified (Table 2) on the basis of their internal structural characteristics (stratification). The stratification of the intrusions and the composition of their constituent mineral associations undoubtedly reflect the common petrochemical characteristics of the rocks and of the magmatic melts from which these rocks evolved. Therefore in our scheme we take into account all the available data on the characteristics of the intrusive massifs. It is also important to stress that stratified massifs referred to different intrusive complexes are usually found in the same locales and appear to have been injected within relatively close time intervals. Furthermore, there are grounds to assume that individual magmatic bodies are products of plutonic differentiation of the same primary basic melt and are therefore sub-phases of the same stage of magmatism.

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* groups? Translator.

These types of stratified intrusions are as follows: fully differentiated intrusions with horizons of basic and ultrabasic rocks; differentiated leucocratic intrusions composed predominantly of basic rocks, but lacking well-developed horizons of ultrabasic rocks; differentiated melanocratic intrusions composed largely of ultrabasic rocks with limited amounts of basic constituents. The major sulphide-bearing intrusions of p.13 the Noril'sk province are the fully differentiated Talnakh, Noril'sk I, Imangdinskii and Chernogorsk intrusions, the differentiated leucocratic Zubovskii and Manturovskii intrusions, and the differentiated melanocratic Nizhne**-Talnakh, Nizhne**-Noril'sk, Burkanskii*, Klyukvennyi*, Zelenaya Griva and other intrusions.

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* Transliteration. Translator.

** Nizhnii=Lower. Translator.

TABLE 2

Sulphide-bearing intrusive traps of the Noril'sk province

Types	The principal differentiated constituents	Sulphide-bearing differentiate
Fully differentiated	Contact gabbro-dolerites, diorites, gabbro-diorites and gabbro; olivine-free and olivine-containing gabbro-dolerites; olivine and olivine-biotite gabbro-dolerites; picrites and troctolites; taxitic and equigranular olivine gabbro-dolerites; contact gabbro-dolerites	Taxitic and equigranular gabbro-dolerites
Differentiated leucocratic	Same as above, but picrites and troctolites are absent or are developed on a very limited scale in the section of these intrusions	Taxitic and equigranular gabbro-dolerites
Differentiated melanocratic	Same as above, but picrites and troctolites predominate in the section of these intrusions, whereas taxitic and equigranular olivine gabbro-dolerites are lacking among their characteristic constituents	Picrites and troctolites

The stratified intrusions found in the Noril'sk province are associated in their absolute majority with the Noril'sk-Kharaelakhskii fault, the most important tectonic structure of that region (fig. 2). The intrusive massifs are localized directly in the fault zone composed of a set of subparallel strike-slip faults. The isolated massifs located outside the main fault zone appear to be controlled by the system of feather faults bearing northeast. The main fields of development of the intrusive massifs are the loci at which the faults are conjugated with the marginal part of the trap depressions. Stratified intrusions have been detected at the points where a) the Noril'sk-Kharaelakhskii fault cuts across the Noril'sk trap depression in its southern (the Zelenaya Griva and Burkanskii intrusions) and northern (the Noril'sk I, Noril'sk II, Chernogorskii, Zubovskii and Nizhne-Noril'sk intrusions) parts; and b) the Noril'sk-Kharaelakhskii fault intersects the Kharaelakhskii trap depression in its southern (the Talnakh and Nizhne-Talnakh intrusions) and, probably, northern part, where there have also been identified several stratified intrusions.

The Keta-Irbinskii fault and a number of its feather joints localized in the western part of the Tunguska syneclise, are also among the tectonic structures controlling the distribution of stratified intrusions in the Noril'sk province. The Imagdinskii, Manturovskii and certain other intrusions (see fig. 1) are known to be associated with it.

From the viewpoint of their morphology all the stratified intrusions have features in common. Fully differentiated and differentiated leucocratic intrusions are bodies of a limited thickness (200-250m or less). In cross section the massifs are lenticular, trough-shaped or (less often) tabular; the outline of their sections may very substantially along the strike and down the dip depending on the structural characteristics of the enclosing rock mass. In the locales of fault flexures or folds the rims of intrusive bodies may rise steeply, in the event of which the transverse section of the intrusions is close to isometric, tubular.* Under relatively calm tectonic conditions the cross sections are for the most part lens-shaped, elongated. Individual transverse sections rarely exceed 1.0-1.5 km in width and commonly measure a mere few hundred meters. Down the dip of the intrusions there may be observed substantial rises and lowerings of the roof, as well as alternating pinch and swell locales.

Differentiated melanocratic intrusions are commonly in the form of sheets. The thickness of the bodies is usually 100-150m or less with occasional swells. In the latter the transverse section of the intrusion may be close to isometric (pipe-like) in outline.

A feature characteristic of the massifs is their separation into a number of discrete, spatially close bodies referred to in the literature as intrusive branches. In the field of development of the intrusion the branches may be spread out in relation to one another to the point of being perpendicular. It is, however, often impossible to prove that the individual branches are interrelated forming an integral intrusion. In some cases the branches are obviously discrete masses formed by independent injections of magmatic melts. The data pertaining to the conditions under which the magmas invaded the horizons where the intrusions are localized, are therefore highly important. As is well known, basic stratified intrusions occur subconcordantly in relation to their host rocks. Similarly to the sedimentary and volcanic rocks, the intrusions pitch towards the central part of the basins at angles equal to the angles of dip of their limbs. If the general dip remains within the 5-15° limits, p.15 the intrusions only occasionally cut across the contacts of concordant sedimentary beds. This attitude of the intrusions and their branches gave rise to hypotheses postulating the migration of trap melts from the central parts of the basins towards their peripheries along the gently ascending feeder channels.

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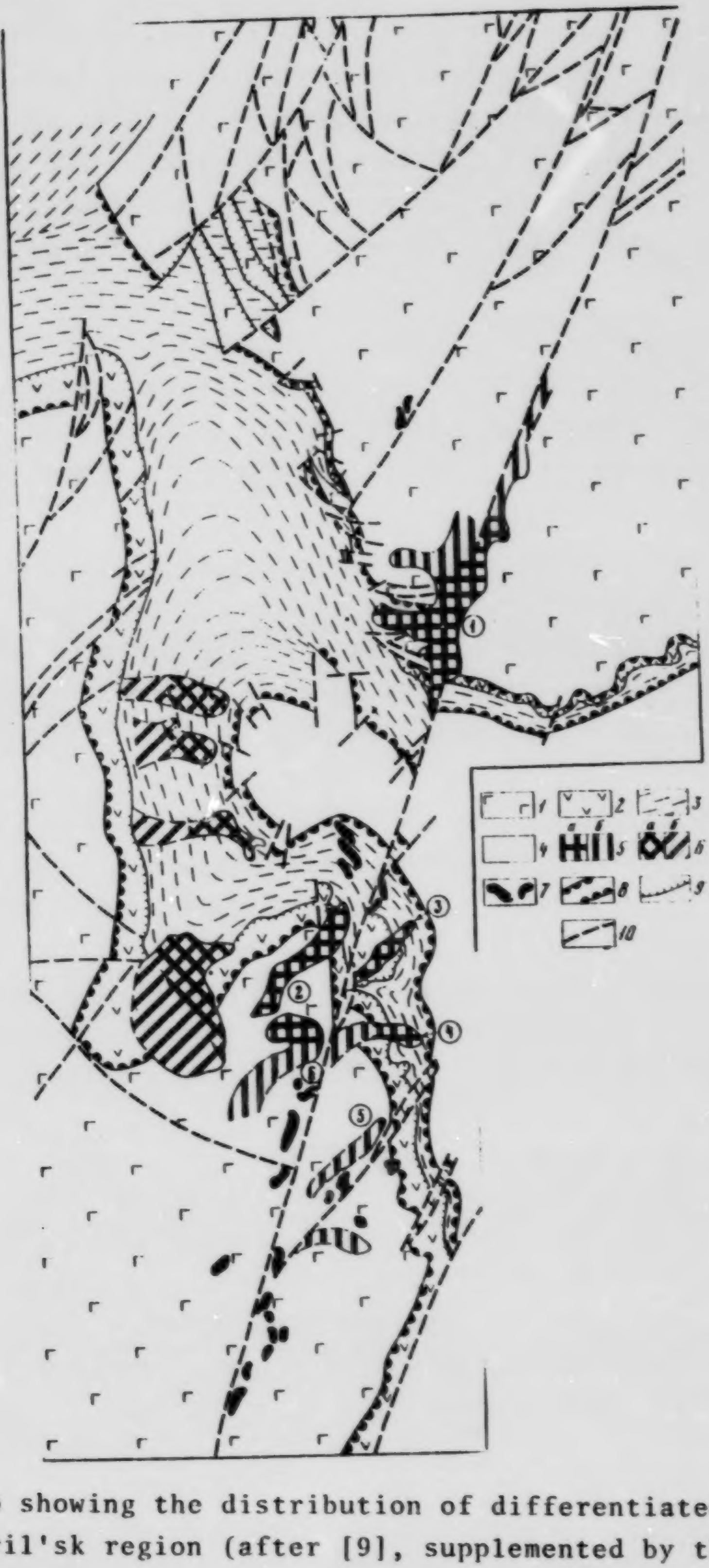
* pipe-like. Translator.

Fig. 2.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Sketch map showing the distribution of differentiated intrusions in the Noril'sk region (after [9], supplemented by the authors)

1,2-The main tuff lava suites (sets): 1-Upper Samoedskii and Nadezhdinskii, 2-Lower Gudzhikhinskii and Ivakinskii; 3,4-Sedimentary and sedimentary-metamorphic beds: 3--D-P_2, 4--- Є-S; 5-7---Differentiated intrusions: 5-Fully differentiated intrusions (figures in the circles): 1-Talnakh, 2-Noril'sk I, 3-Noril'sk II, 4-Chernogorskii, 5-Obeshchayushchii creek, a-established, б-presumed; 6-East Noril'sk, 6-Differentiated leucocratic, a-established, б -presumed, 7-Differentiated melanocratic; 8-Horizon with differentiated intrusions; 9-Boundary of the tuff lava beds with the sedimentary complex; 10-Tectonic disturbances.

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In addition to this there have recently been obtained data characterizing the attitude of the intrusions in relatively deep-seated parts of the trap basins. It has been established that the intrusions pitching towards the centre of the basins in concordance with the general dip of the surrounding rocks may be stratigraphically uplifted into higher stratigraphic horizons of the trap depressions. As a result of this the most markedly downwarped parts of the intrusions are in their centre. Convincing data have been obtained regarding the Noril'sk intrusion. It has been established that even though this intrusion generally dips in the submeridional direction, in the northern and southern parts it is localized in tuff lava horizons, but in the central part it reaches with its base as far down as the horizon of Permian-Carboniferous sedimentary rocks. This sort of features in the attitude of the intrusions suggests that the intrusions may have been injected through subvertical channels controlled with regard to their position by plutonic tectonic zones, rather than by way of low-angle zones from the central parts of the basin. This scheme of intrusion of magmatic melts would enable us to explain many patterns observed in the spatial distribution of compositionally diverse intrusions. For example, the constant association of fully differentiated intrusions with differentiated melanocratic ones and the presence of interlinking subvertical apophyses between them testify to a sequential, but temporally close injection of melts through the same channels. This type of relationship has been quite reliably established between the Talnakh and Nizhne-Talnakh intrusions.

Analysis of the patterns of injection of magmatic melts is important not only for the purpose of explaining the factors governing the localization of intrusions, but also for understanding the zoning in the distribution of ores.

Stratification and cryptic layering

Most of the stratified intrusions have been described in greater or lesser detail in the literature [8,64,65,71,75, etc.]. Fully differentiated intrusions have been examined most thoroughly; differentiated leucocratic intrusions have been described in somewhat lesser detail; and the information pertaining to differentiated melanocratic intrusive bodies is relatively scant.

In characterizing stratification, we focus in particular on cryptic layering of intrusive massifs. Cryptic layering is one of the fundamental properites of stratified complexes [148]. In the literature there are highly interesting reports on the Bushveld complex [186] and Sudbury intrusion [252]. The studies pertaining to the Skergaard complex [148] are among classical works. Data on cryptic layering of some of the intrusions from the Noril'sk province are presented in our work [61].

Fully differentiated intrusions. Structural characteristics of fully differentiated intrusions are examined here on the example of the Talnakh intrusion.

The horizons distinguished in the vertical section of the intrusions are as follows.

The horizon of the upper, contact gabbro-dolerites. The rocks composing this horizon are not uniformly distributed, but commonly occur at the contacts of the intrusions with terrigenous rocks or basalts. The upper, contact gabbro-dolerites are compact massive rocks with a poikiloophitic or ophitic texture. The average composition of the rocks is $Pl^{40-50} + Kpx^{20-25} +$

$+Opx^{1-3} + Amf^{10-15} + 01^{5-10}$[*]. Accessory minerals are represented by magnetite, ilmenite, chromite, apatite, spene (titanite) and biotite. Minor quantities of sulphides may also be present. If hybrid rocks and meta-breccia are found in the roof, then contact gabbro-dolerites may be lacking. p.16

The horizon of quartz-containing gabbro-dolerites, gabbros, gabbro-diorites and diorites. This horizon has been recorded in all the sections of the massifs. Its constituent rocks have a large-grained aspect or (less often) may be inequigranular, ataxic or pegmatoid. Texture prismatic-granular, gabbroid or gabbroid-ophitic. A feature characteristic of these rocks is the invariable presence of quartz. Quartz, intergrown with potash feldspar, forms graphic aggregates filling the interstices between the grains of plagioclase. The average composition of the rocks is $Pl^{50-60} + Kpx^{5-20} + Amf^{10-15} + Q^{5} + Mk^{5-10}$. A feature characteristic of the rocks from this horizon is the extensive development of apatite therein. Accessory minerals are represented by biotite, magnetite, titanomagnetite, sphene and (less often) by sulphides, mainly pyrite. The secondary minerals identified are green hornblende, epidote and zoisite.

The horizon of olivine-free and olivine-containing gabbro-dolerites. The rocks of this horizon differ from the varieties described above because of their finer-grained, equigranular medium-grained aspect. Quartz and micropegmatite aggregates disappear from among their constituents, but there appears instead olivine, which gradually increases in quantity to a concentration of 5-7%. Texture ophitic, poikilophitic or (less often) panidiomorphic-granular; average composition $Pl^{60} + Kpx^{30} + 01^{5} + Amf^{3} + Mk^{2}$. Accessory minerals - apatite, magnetite and titanomagnetite; secondary minerals - iddingsite, bowlingite (saponite), prehnite and chlorite.

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[*] Here and throughout the text the figures indicate volume % of the mineral in the rock.

The horizon of olivinic and olivine-biotite gabbro-dolerites. The rocks of this horizon compose a significant (up to 20-30%) portion of the section in the intrusion. These rocks have been set apart as a separate horizon rather tentatively, since olivine gabbro-dolerites are a regular member of the stratified series, in which olivine steadily increases in quantity towards the central part of the massif. The rocks amalgamated into this horizon contain 10-15% olivine in the upper portion of the horizon and 15-25% olivine in its lower part. The granularity of the olivine gabbro-diorites gradually grows finer relative to that of the rocks from the superjacent horizon. The texture of the rocks is poikilophitic, here and there ophitic. The average composition of the rocks is $Pl^{50} + Opx^{5} + Ol^{15}$. Accessory minerals - biotite, titanomagnetite, magnetite, apatite, amphibole and sphene; secondary minerals - iddingsite, bowlingite, prehnite, chlorite and calcite.

The olivine-biotite gabbro-dolerites differ from the above variety mainly in having a higher content of biotite and somewhat different ratios of the other rock-forming minerals: $Pl^{40} + Kpx^{30} + Opx^{5} + Ol^{20} + Bi^{5}$. The rock texture is poikilophitic. The accessory and secondary minerals are here the same as in the olivine gabbro-dolerites, but a highly characteristic feature of the rocks described is the appearance in them of chromite and sparsely disseminated sulphides.

The horizon of picrite gabbro-dolerites. This horizon is one of the most important components of stratified intrusions. It amalgamates a group of petrographic varieties resembling most closely ultrabasic rocks in their composition. As is well known, the presence of olivine-rich rocks is a feature characteristic of all the stratified massifs from the Noril'sk province, and picrite gabbro-dolerites have been formally identified (25-40% olivine) in nearly all the intrusions. Fully differentiated massifs are, however, the only type of stratified intrusions where these rocks have the distinctive characteristics setting them apart from the other intrusions. These characteristics include the following: 1) The presence of rock varieties corresponding to plagioclase peridotites $(Ol^{70} + Kpx^{15} + Pl^{10} + Opx^{5})$ or plagioclase olivinites $(Ol^{85} + Kpx^{5} + Pl^{5} + Opx^{5})$ in addition to genuine picrite gabbro-dolerites $(Ol^{30-50} + Kpx^{20-30} + Pl^{20-30} + {}+Opx^{5})$; within the horizon there may be found plagioclase-rich rocks close in composition to troctolites $(Ol^{45} + Pl^{10} + Kpx^{10} + {}+Opx^{5})$; 2) The presence in ultrabasic rocks of chromite minerals and of a number of specific minerals of the kind of alkaline amphibole, etc.; 3) Sulphide ores are extensively developed only p.17 in picrites of fully differentiated intrusions.

In the section of fully differentiated intrusions the horizon of picrite gabbro-dolerites occurs below the olivine and olivine-biotite gabbro-dolerites. The contact between the picrites and the overlying horizons is relatively well defined and can be readily fixed by the degree of textural and structural changes, decrease in the size of grains and appearance of sulphide minerals. The total thickness of the picrite horizon is very variable ranging from a few meters to 30-40m. There have been recorded isolated intersections, where it is up to 50-70m. The greatest thicknesses are found in the centre of the intrusive bodies; the horizon commonly thins out towards the flanges of the massifs and is completely lacking in their peripheral parts.

Picrites are the most widely distributed rock variety within the horizon. These rocks have a poikilophitic or segregation texture. Ultrabasic rocks of the type of peridotites and olivinites are found mainly in the central part of the horizon. They form irregularly shaped lenticular or elongated zones occurring amidst picrites, and alternate with the latter. The ultrabasic rocks vary in thickness from tens of centimetres to a few metres. The textures characteristic of the ultrabasic rocks are of the panidiomorphic, poikilophitic and segregation types. In the presence of high concentrations of sulphides the texture of the rocks becomes sideronitic.

It is important to note another aspect of heterogeneity of the picrite horizon: the uneven, non-uniform distribution within the horizon of schlieren-like isometric or irregularly shaped agglomerations of plagioclase or plagioclase and pyroxene referred to in the literature as leucocratic segregations. They commonly measure tens of centimetres. The internal structure of these agglomerations is determined by the presence of idiomorphic crystals of plagioclase and by the sharp xenomorphism of clinopyroxene crystals to the plagioclase. The leucocratic agglomerations are distributed unevenly. In the upper part of the horizon there may be encountered small agglomerations of plagioclase resembling glomeroporphyric concentrations. The leucocratic concentrations increase in number and size in the lower part of the horizon. The largest and most numerous agglomerations are found at the boundary of picrites with taxitic gabbro-dolerites. The largest ones are in the form of subvertical zones with loci of picrites. With further increase in the content of the leucocratic constituent the rocks alter to taxitic gabbro-dolerites.

In a number of locales inside the Talnakh intrusion the rocks of the picrite horizon do not alter directly to taxitic gabbro-dolerites, but are succeeded by highly distinctive rock varieties of the type of evenly large-grained troctolites or olivinic gabbro. These rocks are not characteristic of any of the other stratified intrusions. Their mineral composition varies from $Ol^{30} + Pl^{40} + Kpx^{25} + Opx^{5}$ in troctolites to $Ol^{15} + Pl^{50} + Kpx^{30} + Opx^{5}$ in olivine gabbro. The texture of the rocks is poikilophitic or gabbroid.

The horizon of taxitic and equigranular gabbro-dolerites. Similarly to the rocks of the picrite horizon, the rocks composing the horizon examined are among the most characteristic formations of fully differentiated intrusions. These rocks differ from picrites and from the olivine gabbro-dolerites occurring at a higher level, in that plagioclase and clinopyroxene predominate in them over olivine. The presence of these rocks in the lower part of the massifs accounts for the inversion of the quantitative mineral composition of the intrusions. Whereas in the upper part of the intrusions the quantity and relative content of the ultramafic mineral association distinctly increase from the roof towards the picrite horizon, below that horizon the quantity and percentage of that mineral association progressively decrease. It is highly significant that variations in the granularity of the rocks coincide with these changes. For example, while the rocks of the picrite horizon are the finest-grained varieties, above and below that horizon the rocks have a larger-grained aspect. In the direction of the upper contact the granularity p.18 increases relatively smoothly and gradually, but towards the lower contact the changes in the grain size are sharper.

In most of the intrusions taxitic gabbro-dolerites are represented by sharply inequigranular ataxitic large- to giant-grained, here and there pegmatoid, rocks. They are of a breccioid aspect, particularly in the lateral parts of the intrusions, and abound in xenoliths. All the varieties listed above may be found within one single lump of ore of a moderate size. Giant-grained pegmatoid loci may be surrounded by a fine-grained or evenly medium- grained mineral aggregate. Textural characteristics of the rock are clearly observable in thin sections. Large-grained loci composed of plagioclase-pyroxene with a poikilophitic or hypidiomorphic texture are found in combination with fine-grained isometric or even veinlet-like agglomerations of plagioclase-olivine or plagioclase-pyroxene with a micro-granoblastic texture. Olivine may be present in the large-grained aggregates in the form of poikilotopic (poikilocrystallic) or idiomorphic and isometric grains, as well as in the fine-grained mass, where it forms small spherical grains. The forms characteristic of plagioclase are broad tabular or large slender elongated crystals, as well as small isometric granular bodies (grains). Pyroxenes are found for the most part in the form of poikilocrysts, but may occasionally form isometric or idiomorphic crystals. The textural characteristics of the rocks listed above account for the textural diversity of the rocks and their sharply ataxic fabric, as well as for the development of poikilophytic, ophitic, hypidiomorphic, gabbroid, pegmatoid and granoblastic textures therein.

The textural non-uniformly of the rocks is also due to the heterogeneity of their mineral composition. Even though plagioclase is invariably the essential mineral in these rocks, its content may vary from 40 to 70%. The content of clinopyroxene varies from 15 to 35%. The most unevenly distributed mineral is olivine and its concentration varies from single grains to 30%. Orthopyroxene occurs sporadically and amounts to no more than 3-5%. Accessory minerals are represented by amphibole, biotite, magnetite, titanomagnetite, ilmenite and apatite. Sulphides are invariably present. In contrast to the rocks of the picrite horizon, taxitic gabbro-dolerites contain no chromite.

Evenly medium-grained olivine, olivine-containing or even olivine-free quartzose gabbro-dolerites may be found among the constituents of the horizon examined in the bottom part of the intrusions, below taxitic gabbro-dolerites or (less often) instead of them. These rocks have ophitic or poikilophitic textures because of the presence of idiomorphic tabular plagioclase crystals and xenomorphic crystals of clinopyroxene. Olivine may be present in these rocks in the form of isometric grains or poikilocrysts. The quantitative mineral composition of the rocks is close to that of taxitic gabbro-dolerites: $Pl^{50} + Kpx^{25} + Opx^{5} + Ol^{20}$. A characteristic feature of the rocks is the presence of subcalcium augite in addition to clino- and orthopyroxene. Augite is found in clinopyroxene in the form of tabular crystals and appears to be a product of exsolution. Accessory minerals are represented by the association characteristic of taxitic gabbrodolerites. These rocks also contain sulphides. When sulphides are present in large quantities, the texture of the rocks becomes siderenitic.

The horizon of contact and porphyroid gabbro-dolerites. Contact gabbro-dolerites complete the section of intrusive massifs. From the viewpoint of their texture and essential mineral composition these rocks are very close to the upper

contact gabbro-dolerites examined earlier. The main differences between them are the somewhat higher content of olivine and sporadically ataxic texture of the lower contact rocks. The average quantitative mineral composition is $Pl^{50} + Kpx^{30} + 01^{20}$. The accessory and auxiliary minerals are represented by amphibole, biotite, apatite, sphene, magnetite, titanomagnetite and relatively small amounts of sulphides. The texture is poikilophitic or doleritic at the very contact with the host rocks. p.19
The horizon is up to 2-3m in thickness.

Several drill holes revealed highly distinctive rocks in the Talnakh intrusion, in the locales adjoining the zone of the Noril'sk-Kharaelakhskii fault. These rocks are represented by markedly porphyritic gabbro-dolerites with large (up to 1cm) phenocrysts and glomerophyric intergrowths of basic plagioclase set in a fine- or small-grained dolerite groundmass. Microscopic analyses show that the insets are represented by thick tabular or, less often, elongated idiomorphic grains corroded by the groundmass. In the glomeroporphyric intergrowths the groundmass penetrates inbetween the individual grains of plagioclase. Individual crystals may be bent or displaced. These features suggest that the porphyritic phenocrysts are among the earliest protocrystals separated from the magmatic melt. The groundmass of the rocks is fully crystallized and is composed of small laths of plagioclase, xenomorphic crystals of clinopyroxene and isometric or, less often, xenomorphic grains of olivine. Unlike the contact gabbro-dolerites, these rocks contain virtually no sulphides. The porphyritic gabbro-dolerites form gradual transitions with the overlying rocks.

Wherever porphyritic gabbro-dolerites are found at intersections of intrusions, they have an apparent thickness of 10-20m. It is important to note that rocks of that kind have also been identified in the dike-like body ajoining the lower contact of the Talnakh intrusion. These bodies occur in the same locales as porphyritic gabbro-dolerites. One of the dike-like bodies penetrated by several drill-holes, has a relatively flat (low-angle) attitude with a 30-40° angle of dip.

The body measures about 10m in thickness. Down the dip it appears to go over into the Nizhne-Talnakh differentiated melanocratic intrusion. In our opinion the rocks described and the dike-like bodies composed of these rocks may be products of the feeder channel for at least one of the branches of the Talnakh intrusion.

We have thus examined the structure of the section characteristic of the type of intrusions described. The stratification and certain other distinctive features of structure, are somewhat different in the flanges of the intrusions, particularly in the so-called frontal zones. Structural characteristics of the frontal zones in these intrusions are distinctly controlled by the lithology of the country rock . The most intricate types of structure have been observed in the parts of the intrusion localized in sulphate-carbonate beds, and significantly simpler ones in the frontal zones enclosed in carbonaceous terrigenous or volcanic deposits.

In sulphate-carbonate rocks the massif usually splits up into a multitude of subparallel apophyses measuring several tens of centimetres to tens of metres. This type of ramification has been recorded in the northwestern branch of the Talnakh intrusion and in the Imagdinskii intrusion. The predominant rock varieties in most of the apophyses are ophitic or poikilophitic olivine-containing or olivine gabbro-dolerites. Among the apophyses the largest ones may display a similitude of stratification with olivine-rich rocks concentrating at the bottom. However, no rocks corresponding to picrite gabbro-dolerites have been observed in the apophyses. In the bodies with a small thickness the most widely distributed rocks are micro-dolerites with vitric chilled contact zones. The micro-dolerites correspond in composition to olivine-containing and olivine varieties of gabbro-dolerites. In the locales with extensively developed microdolerites the whole contact zone of the intrusion has a distinctly breccioid appearance. "Fragments" of magmatic materials alternate there with sedimentary-metamorphic products, and the true correlation of heterogeneous materials is substantially obscured by the presence of a secondary metasomatic rock complex. The complexity of the fabric in such zones gave rise to several concepts interpreting the origin of the breccioid rocks in different ways. Explosion brecciation is one of the hypotheses put forward [119]. It has been suggested that these rocks, referred to as pseudobreccias of pseudotachylites, are products of the high-temperature postmagmatic fusion [75]. p.20

Microdolerites are found mainly in the upper part of the intrusive body. Rocks identical in texture and composition to taxitic or equigranular gabbro-dolerites are a major constituent of the contact zone, in its bottom part, of the massif. These rocks enclose a profusion of xenoliths of the wall rocks and form themselves branching veinlets of a variable thickness with signs of replacement of the country rocks.

In examining the contact zone of fully differentiated massifs and in interpreting the processes occurring in zones of that kind we must not ignore the structural characteristics observed in analogous contact parts of the intrusions localized in terrigenous or volcanic rocks. The flanges of the latter intrusions have invariably a much simpler structure. Their contact zone is commonly free of brecciation phenomena, and formation of microdolerites is not characteristic of that zone. In addition to olivine, olivine-containing equigranular and taxitic varieties of gabbro-dolerites, there have also been encountered picrite gabbro-dolerites. The intrusions pinch out relatively smoothly: the body decreases in thickness and changes to a tabular sill. This is the structure of the flanges in the branch of the Talnakh intrusion that occur amidst Permian-Carboniferous terrigenous deposits, and of the Noril'sk intrusion localized in extrusive rocks.

It should be emphasized that the features of structure described above for the contact zones of intrusive bodies emplaced in various rocks, are characteristic not only of fully differentiated intrusions, but have been observed in nearly all the differentiated and undifferentiated massifs. Wide-spread brecciation, formation of microdolerites and highly complex structures of contact zones have been recorded in the intrusions localized in the sulphate-carbonate rocks from the southern part of the Noril'sk trap depression, in the north of the Kharaelakhskii basin, and in a number of other locales. In some of the drill-holes in the north of the Kharaelakhskii trap depression the breccioid rocks and the zones with microdolerites associated with undifferentiated intrusions of olivine gabbro-dolerites, attain 150-300m in thickness; in association with differentiated melanocratic intrusions there have been established zones of breccias with thicknesses up to 50-100m.

All this suggests that the formation of breccioid rocks composed of fragments of intrusive and altered sedimentary materials with a significant percentage of secondary hydrothermal-metasomatic products, cannot be regarded as a specific feature of the formation of sulphide-bearing intrusive traps. The most important factor is probably the composition of the host sediments, which interact with magmatic melts and determine not only their crystallization pattern, but to some degree even the composition of these melts. A possible interpretation of the contact interaction between the intrusions and the country rock will be discussed farther on.

Cryptic layering. As was mentioned earlier, cryptic layering is the most important index among the factors characterizing sulphide-bearing traps. It manifests itself in characteristic changes of the mineral composition in the section of the intrusion as a whole and in its individual horizons; in the distribution of components among the coexisting mineral phases; and in the patterns of appearance and disappearance of different minerals.

As was pointed out in the work by V.V. Distler et al. [61], the most important characteristics of cryptic layering in fully differentiated intrusions are: 1) The extreme shape of the curves depicting variations in the composition of the coexisting minerals, with the characteristic flexure at the point corresponding to the central part of the ultrabasic horizon; and 2) The relatively narrow range of variations in the mineral composition of most of the horizons in the intrusions. p.21

The most important variations in the composition of essential minerals are summarized in Table 3 and in the diagrams (figs. 3 and 4) prepared on the basis of the vast analytical material published earlier [6 and 75].

TABLE 3

Chemical composition of olivines from differentiated intrusions (weight %, X-ray microanalysis)

Sample numbers	Rocks	SiO_2	FeO	MnO	MgO	CaO	NiO	Cr_2O_3	TOTAL
ST-8	Upper contact gabbro-dolerite	35.6	30.1	0.53	30.8	0.17	0.06	0.02	97.28
731/863.8	Olivine gabbro-dolerite	37.3	26.7	0.54	35.3	0.20	0.09	0.02	100.15
		37.0	27.5	0.55	34.5	0.25	0.09	0.02	99.91
731/876.0	Same as above	37.2	24.7	0.58	38.1	0.20	0.12	-	100.90
731/900.7	Picrite gabbro-dolerite	38.8	18.2	0.32	41.04	0.2	0.17	-	98.73
731/909.3	Same as above	36.5	18.8	0.27	42.6	0.17	0.17	0.02	98.53
731/912.8	" " " "	36.1	20.4	0.42	40.3	0.14	0.25	0.02	97.63
731/921.8	Taxite gabbro-dolerite	36.2	26.7	0.59	34.9	0.21	0.16	0.02	98.78
731/936.0	Same as above	35.3	34.3	0.67	26.7	0.19	0.15	-	97.31
731/940.1	Contact gabbro-dolerite	34.7	37.3	0.65	26.7	-	0.09	-	99.4
IM-39/212	Olivine gabbro-dolerite	39.8	21.86	-	36.69	0.25	0.05	0.06	101.71
IM-39/222.0	Olivine gabbro-dolerite	37.6	25.0	0.41	36.7	0.30	0.12	0.02	100.13
		37.7	23.5	0.38	37.6	0.34	0.13	0.03	99.65
IM-39/234.5	Troctolite gabbro-dolerite	38.08	24.07	-	37.0	0.22	0.06	0.02	99.71
IM-39/256.0	Same as above	37.0	22.37	0.40	40.1	0.16	-	-	100.03
		38.5	19.04	0.38	41.18	0.16	-	-	99.26

(Table 3, continued)

IM-39/265-0	Picrite gabbro-dolerite	40.33	17.02	-	42.41	0.14	0.13	0.03	100.24
IM-39/287.0	Taxite gabbro-dolerite	37.37	29.62	-	32.21	0.16	0.18	-	99.88
NP-13/1229	Olivine gabbro-dolerite	39.3	18.8	0.25	42.6	0.36	0.07	-	100.05
NP-13/1238.5	Troctolite gabbro-dolerite	38.5	18.7	0.21	42.7	0.34	0.08	-	100.05
NP-13/1262.0	Picrite gabbro-dolerite	38.7	18.8	0.24	41.1	0.20	0.06	-	99.12
NP-13/1268.0	Troctolite gabbro-dolerite	41.0	19.3	0.28	40.9	0.34	0.07	-	101.9
NP-13/1276	Picrite gabbro-dolerite	38.0	18.1	0.27	43.5	0.29	0.06	-	100.24
NP-13/1284	Contact gabbro-dolerite	39.7 38.8	16.7 20.9	0.27 0.31	42.4 39.8	0.39 0.36	0.07 0.09	- -	99.55 100.28

FOOTNOTES. Samples ST-8 - 731/940.1 from the Talnakh intrusion; IM-39/212 - IM-39/287 from the Manturovskii intrusion; NP-13/1229 - NP/13/1284 from the Nizhne-Noril'sk intrusion.

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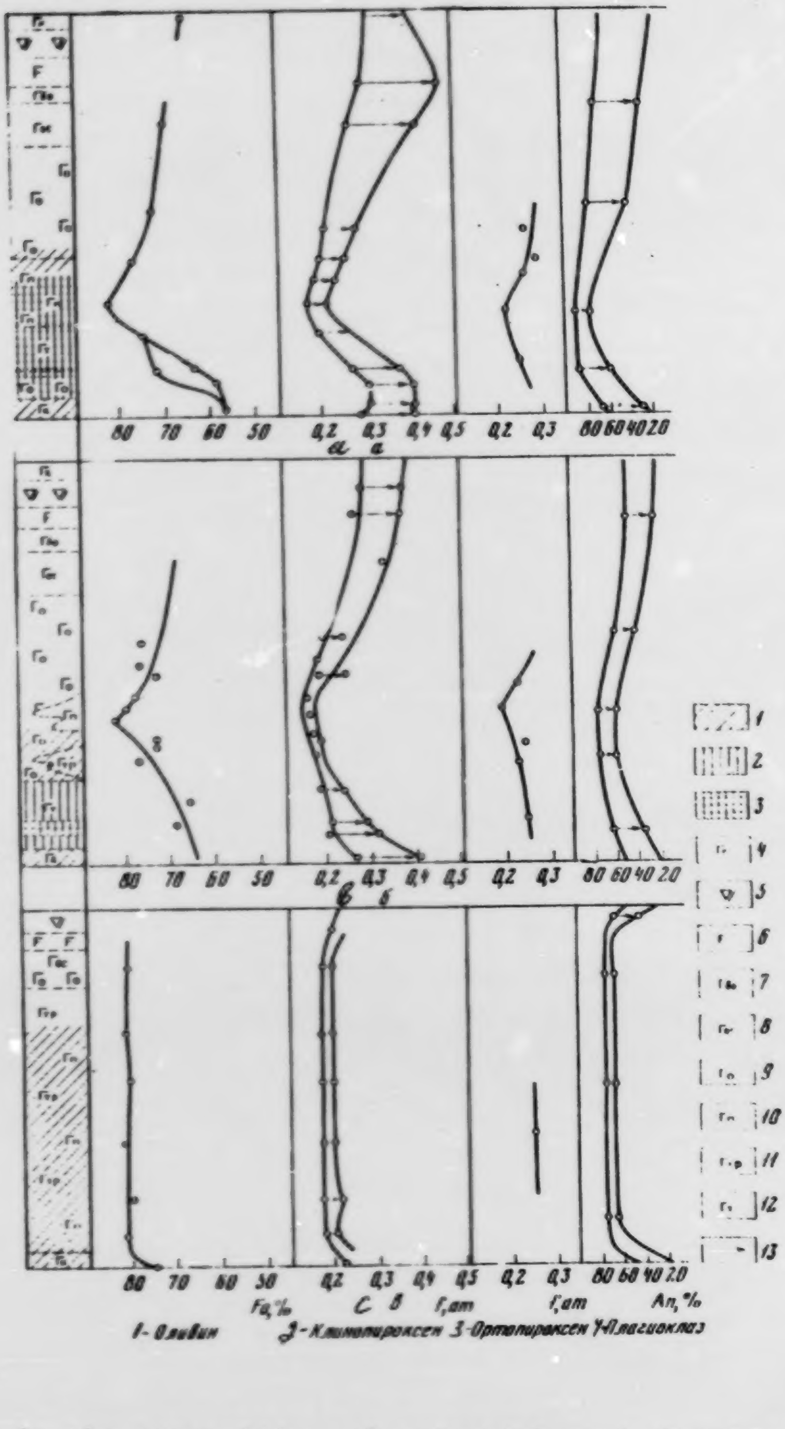
Olivine. The composition of olivine varies within a fairly large range from Fo_{43} to Fo_{82}. The least ferruginous olivine with the composition Fo_{82} is found in the central part of the picrite horizon. Its content of iron distinctly tends to increase towards p.23 the upper part of the horizon (to Fo_{76}) and towards its bottom part (to Fo_{73}) in troctolites. Olivine gabbro-dolerites commonly contain two varieties of olivine that are close to Fo_{70} and Fo_{66} in composition. The total range of variations in the composition of this mineral from olivine-containing gabbro-dolerites is Fo_{73} - Fo_{66}. In the upper contact gabbro-dolerites its composition is Fo_{65}.

Fig. 3



Variations in the composition of essential rock-forming minerals and distribution of sulphide mineralization in the section of fully differentiated (a), differentiated leucocratic (b) and differentiated melanocratic (c) intrusions. 1-Olivine; 2-Clinopyroxene; 3-Orthopyroxene; 4-Plagioclase.

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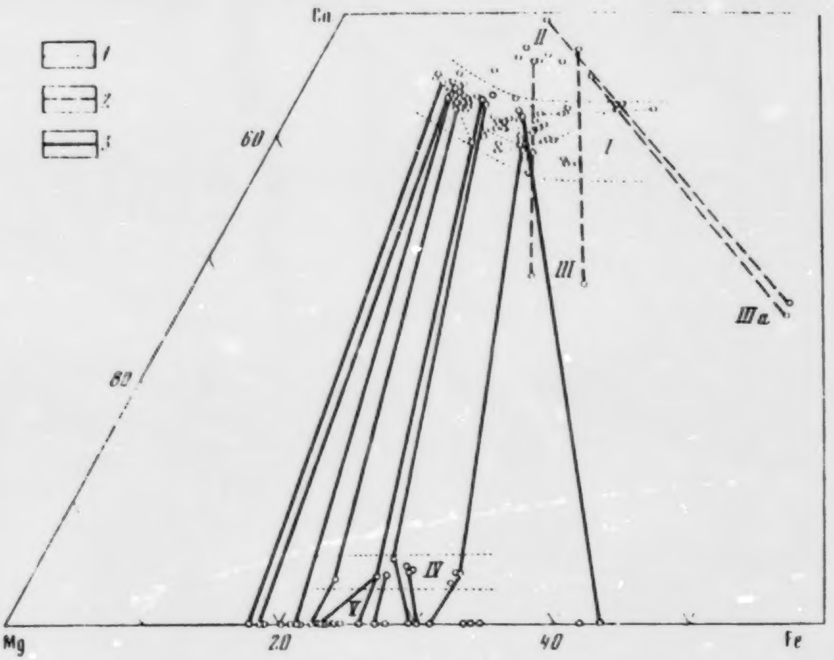
Fig. 4



Diagrammatic representation of the composition of the coexisting minerals from different horizons of the Talnakh intrusion.
1-The composition of the central and peripheral parts of zoned augite crystals; 2-Coexisting sahlites and subcalcium augites;
3-Coexisting augites, orthopyroxenes and olivines;
I-Augites; II-Sahlites; III and IIIa-Subcalcium augite and ferriaugite; IV-Orthopyroxenes; V-Olivines;

1-3---Contents of disseminated sulphides:
1-Very low; 2-Low; 3-High;
4-12---Horizons of differentiated intrusions:
4-Contact gabbro-dolerites; 5-Diorites; 6-Gabbro; 7-Olivine-free gabbro-dolerites; 8-Olivine-containing gabbro-dolerites; 9-Olivine gabbro-dolerites; 10-Picrites; 11-Troctolites; 12-Taxitic gabbro-dolerites; 13-Composition of central and peripheral parts of zoned crystals.

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The least stable composition of olivine has been recorded in taxitic gabbro-dolerites containing crystals of Fo_{74-75} and other varieties of olivine up to Fo_{55}. In our opinion this large range of compositions is a logical development. This horizon should contain olivines representing the early cumulative phases. Crystallization of these phases into the melt of the lower horizons that is not at equilibrium with picrites, predetermine the solution of the early phases and crystallization of the more markedly ferruginous olivines that are at equilibrium with that melt. The crystals corresponding to these phases are apparently those of Fo_{60-70}. The general tendency of the magnesium content in olivine to decrease towards the lower contact of the massif is reflected by the phases with the composition Fo_{55}. The content of magnesium continues to decline in the underlying horizons that are composed of equigranular olivine gabbro-dolerites with the most markedly p.24 ferruginous olivine Fo_{43}.

The lower chill zone contains olivine Fo_{56} (see Table 3).

Clinopyroxene is represented in the intrusions by augite. Variations in its composition generally follow the same pattern as those recorded in the composition of olivine, and the curve depicting variations in the content of iron Kpx (fig. 3) also has its minimum in the picrite horizon (f_{at} =0.18). The concentration of iron in the mineral progressively increases towards the upper and lower contacts of the massif. An important characteristic of clinopyroxenes from all the horizons is the zonal structure of their grains. Variations in the content of iron have been observed in the inner parts of the zoned crystals that are richer in magnesium, as well as in their magnesium-poorer outer parts. As is shown in the work [58], the greatest variations in the content of iron in the outer zone have been observed in the upper horizons (e.g. from f_{at} =0.27 to f_{at} =0.33), and the least significant ones in the hyperbasic horizon (f_{at}=0.18 to f_{at}=0.21). In the former horizons they occur on account of variations in the Mg and Fe ratio at a constant Ca content, and in the hyperbasic horizon - in the Ca and Fe ratio at a constant

Mg. The outer and inner zones of the crystals also differ significantly in their concentrations of alumina, titanium and chromium. The more markedly ferruginous outer zones of the crystals are richer in titanium, but their inner zones contain higher concentrations of alumina and chromium. The highest total concentration of alumina in Kpx is found in the picrite horizon and decreases towards the contact zones of the intrusion (Table 4).

An important feature of variations in the composition of Kpx in different horizons of the intrusion is that the total range of variations in the concentration of iron in the central parts of the crystals is the smallest in picrite gabbro-dolerites, but increases in the overlying and subjacent horizons. This fully agrees with the variations recorded in the composition of the olivine coexisting with Kpx in the same horizons. For example, in the horizon of taxitic gabbro-dolerites there have been encountered Kpx varieties with f_{at} ranging from 0.20 that is characteristic of picrites, to 0.33. The least ferruginous clinopyroxenes appear to correspond to the cumulative grains which crystallize and become deposited together with olivine, whereas the clinopyroxenes with higher concentrations of iron crystallize from the melt at a later stage. It may therefore be assumed that at least the inner magnesian parts of clinopyroxene crystals are at equilibrium with olivine. The outer parts of the crystals and the crystals of clinopyroxenes with higher concentrations of iron are probably at equilibrium with later minerals, including plagioclase. This is also supported by the redistribution of alumina among the clinopyroxenes with varying concentrations of iron.

A specific feature of layering in the intrusions is the formation in the upper and lower quartz-bearing horizons of calcium-rich clinopyroxenes containing subcalcium augite and ferriaugite as products of unmixing. The products of exsolution are invariably richer in iron and their content of alumina is an order higher (Table 5).

Orthopyroxene is a distinctly minor phase and appears to play a subordinate role in the crystallization process of the intrusions. It has been suggested [138] that Opx is a specific buffer phase maintaining/at a definite level/the chemical potential of alumina/in the process of crystallization of olivine. There have, however, been established systematic variations in the composition of that mineral in different horizons of the massif. The total range of variations in the concentration of iron in Opx is relatively small compared to that of olivine. In orthopyroxenes f_{at} varies from 0.26 to 0.32. It should be stressed that the contents of iron are invariably greater in Opx than in Kpx from the same horizon.

As is also the case with the other minerals, the lowest iron concentrations have been recorded in Opx from picrite gabbro-dolerites and the highest ones in Opx from olivine and taxitic gabbro-dolerites (see Table 4).

Plagioclase. Plagioclase crystallized throughout the existence of the melt, as a result of which its composition and p.27 the morphology of its grains vary much more markedly than those of the other minerals. The total range of variations in the composition of this mineral is An_{20} to An_{90}. Plagioclase crystals invariably have a normal zonal structure in all the horizons of the intrusions. The smallest differences in the composition of the zones have been recorded in the ultrabasic horizon An_{65-90}; in all the other horizons the differences are more substantial. Crystals with the composition An_{93} in their central part have been identified in picrite gabbro-dolerite. Furthermore, grains with that composition have been encountered in taxitic gabbro-dolerite, which also contain, however, plagioclases An_{40}. The work [132] discusses the compositional relationship of Pl and Kpx with regard to their (Ca+Na+K) / Al and Si/Al ratios. The data on the composition of clinopyroxene presented in Table 4 suggest that this correlation is only characteristic of later clinopyroxene crystals or of the outer zones of zoned crystals, but not of their central zones that are at equilibrium with olivine. The association of ferruginous Kpx with Pl corresponds to the eutectoid composition of the melt, and magnesian Kpx crystallizes together with with Ol from a supereutectoid melt.

TABLE 4

Chemical composition of clinopyroxenes and orthopyroxenes from differentiated intrusions (weight %, X-ray microabalysis)

Sample numbers	Rocks	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Cr_2O_3	NiO	Total	f_{at}
ST-8	Upper contact gabbro-dolerite	51.8	0.52	2.2	7.5	0.12	15.4	21.5	0.35	0.73	-	100.12	0.21
731/776.6	Diorite	53.8	0.34	2.0	9.5	0.14	15.1	19.9	0.48	-	-	101.26	0.26
		53.2	0.39	1.80	11.8	0.17	14.4	19.5	0.52	-	-	101.78	0.31
731/781.6	Quartz diorite	54.0	0.47	2.0	10.0	0.14	15.4	18.6	0.71	-	-	101.32	0.27
		53.6	0.58	2.1	12.1	0.23	13.9	19.3	0.36	-	-	102.17	0.33
731/813.4	Olivine-free gabbro-dolerite	53.0	0.49	2.1	10.0	0.11	14.9	19.0	0.30	-	-	99.9	0.26
		53.5	0.48	2.1	11.0	0.13	13.6	18.5	0.35	-	-	99.65	0.31
731/815.5	Same as above	53.0	0.43	2.1	11.2	0.11	13.4	19.7	0.27	-	-	100.21	0.31
		52.5	0.41	1.5	14.5	0.24	11.5	19.9	0.18	-	-	100.73	0.41
731/847.3	Olivine-biotite gabbro-dolerite	53.9	0.46	2.3	8.0	0.28	15.8	20.5	0.44	0.30	-	101.98	0.22
731/863.8	Olivine-gabbro-dolerite	55.9	0.52	1.1	17.6	0.16	23.1	2.1	-	-	0.02	100.5	0.20
731/867.3	Same as above	53.1	0.48	3.4	7.9	0.15	15.5	20.6	0.31	0.51	-	100.95	0.22
		56.1	0.57	1.1	16.2	0.18	23.8	2.2	0.12	-	-	100.25	0.28
731/876.0	" " " " "	53.6	0.48	2.4	7.7	0.18	15.4	20.6	0.47	0.29	0.02	101.14	0.22
		56.5	0.47	1.1	14.9	0.55	23.4	1.9	0.08	-	0.02	98.92	0.26
731/880.0	" " " " " "	56.2	0.53	0.82	16.8	0.12	24.9	2.5	-	-	-	101.87	
		52.2	0.42	2.6	8.2	0.10	15.3	21.0	0.42	-	0.03	100.27	0.28
731/900.7	Picrite gabbro-dolerite	51.7	0.41	2.8	6.3	0.18	16.0	21.7	0.29	0.83	0.01	100.22	0.18
731/901.6	Same as above	51.2	0.54	2.7	6.7	0.41	14.8	20.0	0.20	0.91	0.02	97.48	0.20
731/908.9	Same as above	53.4	0.47	2.7	6.5	0.09	15.1	20.9	0.41	0.25	-	99.82	0.19
731/909.3	" " " " "	51.6	0.42	2.8	6.9	0.29	15.4	20.8	0.32	0.68	0.01	99.21	0.20

(Table 4, continued)

731 912.8	" " " " "	52.3	0.53	2.4	7.1	0.21	14.9	21.1	0.23	1.2	0.02	99.99	0.21
731 921.8	Taxite gabbro-dolerite	53.2	0.57	1.6	9.4	0.34	15.6	19.5	0.28	0.09	0.02	100.60	0.25
731 928.5	" " " " "	56.1	0.41	0.92	19.5	0.25	22.9	1.8	-	0.09	0.05	102.02	0.32
		56.2	0.41	0.82	19.4	0.25	23.2	1.8	-	0.09	0.05	102.22	0.31
		53.5	0.63	1.5	11.5	0.19	13.5	19.7	0.33	0.07	0.03	100.92	0.32
731 936.0	" " " " "	53.2	0.57	1.1	10.2	0.40	14.6	19.2	0.44	0.08	0.02	99.81	0.28
731 940.1	" " " " "	52.5	0.51	1.9	10.1	0.35	14.5	19.5	0.14	0.12	0.01	99.63	0.28
IM-39 91.3	Gabbro	51.5	0.060	2.4	11.0	0.17	14.0	20.0	0.50	0.10	0.02	100.29	0.31
		51.0	0.70	1.60	13.7	0.20	13.2	20.0	0.50	0.04	0.01	100.95	0.37
IM-39 154.0	Diorite	50.5	0.47	1.19	15.44	-	15.03	16.03	0.27	0.01	0.015	98.96	0.37
		51.17	0.52	2.04	11.69	-	14.58	19.92	0.37	0.07	0.015	100.37	0.31
IM-39 222.0	Olivine-gabbro-dolerite	51.1	0.72	1.5	12.1	0.13	13.9	20.0	0.51	0.07	-	100.03	0.33
IM-39 256.0	Troctolite gabbro-dolerite	51.8	0.52	2.2	7.5	0.12	15.4	21.5	0.35	0.73	-	100.12	0.21
		51.3	0.60	1.90	7.7	0.15	16.0	21.0	0.37	0.63	-	99.65	0.21
IM-39 300.2	Contact gabbro-dolerite	51.52	0.58	2.56	9.26	0.22	14.02	21.16	-	0.10	0.01	99.43	0.27
		51.22	0.66	1.73	13.81	0.28	11.42	20.72	-	0.06	0.02	99.92	0.40
NP-13 1225.0	Olivine-containing gabbro-dolerite	53.6	0.25	2.08	5.72	0.07	15.40	21.53	0.28	-	-	98.93	0.17
NP-13 1229.0	Olivine-gabbro-dolerite	53.4	0.35	1.68	6.42	0.14	15.68	21.99	0.27	-	-	99.93	0.19
NP-13 1238.5	Troctolite gabbro-dolerite	52.9	0.44	1.96	6.60	0.14	16.2	21.30	0.29	-	-	99.88	0.18
		52.9	0.65	1.86	7.13	0.19	15.8	21.17	0.27	-	-	99.92	0.20
NP-13 1262.0	Picrite gabbro-dolerite	53.3	0.31	2.39	6.76	0.19	16.0	20.69	0.33	-	-	99.97	0.18
		53.3	0.36	1.96	6.82	0.10	15.8	21.08	0.23	-	-	99.65	0.19
		53.8	0.46	1.06	15.7	0.29	25.9	1.56	0.10	-	-	98.90	0.25

(Table 4, continued)

NP-13 1268.0	Troctolite gabbro-dolerite	52.5 52.6	0.40 0.57	1.62 1.82	6.60 7.59	0.17 0.19	16.4 15.8	21.94 21.17	0.26 0.27	- -	- -	99.89 100.01	0.18 0.21
NP-13 1276.0	Picrite gabbro-dolerite	53.3 53.2	0.36 0.36	2.0 2.02	6.6 6.7	0.12 0.17	17.0 16.31	20.6 21.12	0.23 0.15	- -	- -	100.21 100.03	0.18 0.19

FOOTNOTE. Samples ST-8 - 731/940 from the Talnakh intrusion, IM-39/91.3 - IM-39/300.2 from the Manturovskii intrusion, and NP-13/1225.0 - NP-13/1276.0 from the Nizhne-Noril'sk intrusion.

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TABLE 5
Chemical composition of subcalcium augites and ferro-augites (weight %, X-ray microanalysis)

Intrusions	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Cr_2O_3	NiO	Total	f_{at}
Talnakh	53.2	0.50	0.78	15.1	0.40	16.2	13.8	0.44	0.08	0.02	100.54	0.34
Manturovskii	49.4	0.75	0.23	19.9	0.23	10.3	15.5	0.55	0.28	0.03	97.14	0.52
Nizhne-Noril'sk	49.6	0.45	4.30	24.9	0.34	9.10	11.4	0.32	-	0.03	100.44	0.60
	52.7	0.07	4.20	16.1	0.25	14.0	12.2	1.10	-	0.03	100.65	0.39
	53.7	0.39	2.90	13.7	0.15	15.8	10.8	0.36	-	-	97.80	0.33

Chrome-spinellids and spinels. Minerals of this group are among the most important indicators of the magmatic melts forming fully differentiated traps. Among the multitude of trap intrusions, chromites are found, for example, exclusively in the type of intrusions examined [41]. Furthermore, the association of magnesian olivine with magnesian-aluminiferous spinel is known only from these intrusions [138]. Lastly, in the upper horizons of the Talnakh intrusion there has been identified hercynite, a ferruginous* spinel that has not been encountered in any of the other types of intrusions. It is important to stress that the association of chromite and copper-nickel sulphide ores is characteristic of a number of stratigraphic complexes, such as Stillwater [231], Bushveld [187], etc. It is therefore imperative to analyze in detail the characteristics of the spinels found in fully differentiated traps.

Increased concentrations of chromium are generally characteristic of this type of intrusions. At different stages of crystallization chromium becomes fixed in silicate phases, mainly in clinopyroxenes, or forms a spinel phase proper. Chromite minerals concentrate in the Noril'sk I, Imagdinskii and Talnakh intrusions in the picrite horizon, but single grains of chromium-containing spinel phases have also been identified in other horizons.

Chromites have been encountered in the form of small isolated idiomorphic crystals in the chilled facies of the intrusions, i.e. in contact gabbro-dolerites. Sparsely distributed grains of chromite appear in olivine-rich parts of the horizon of olivine gabbro-dolerites adjoining the horizon of ultrabasic rocks. The maximum amount of chromite has been recorded in the picrite horizon.

In picrites and other rock varieties of the ultrabasic horizon there have been distinguished two types of chromite minerals. The first type is represented by relatively uniformly distributed small idiomorphic or spherical grains of chromite forming inclusions in all the rock-forming minerals. The second one forms isometric agglomerations abounding in chromite and p.28 measuring a few centimetres to several tens of centimetres or (very rarely) even up to 1m. These concentrations are confined mainly to the bottom part of picrite gabbro-dolerites.

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*ferroan. Translator.

Among the disseminated chromite there may be distinguished two types of grains. The first type is represented by small dark spherical isometric grains forming insets in olivine, clinopyroxene and plagioclase. The second type forms regular idiomorphic crystals of a lighter colour. Light-coloured chromite may overgrow mafic chrome-spinellids. The correlation permits us to determine the age relationship of the chromites: the dark-coloured (mafic) chromites forming spherical grains are probably earlier formations than the light-coloured ones.

The agglomerations of chromite are among the most striking formations in the ultrabasic horizon of fully differentiated intrusions. The concentration of chromites in these agglomerations attains 25-30% of their volume. The boundaries of the agglomerations with the host rocks are extremely sharp and clearly defined. Gradual transitions from this type of mineral agglomerations to the disseminated type of concentrations are unknown. The rock-forming minerals (among which plagioclase and clinopyroxene predominate, while olivine is found rarely) may, however, penetrate inside such concentrations with a portion of their crystal, which abounds then in chromite inclusions, while the rest of the crystal remains outside the agglomeration and contains no inclusions of chromite. It should be noted that the rock-forming silicates associated with chromite agglomerations are commonly larger than the silicates found in the surrounding country rock.

The most important characteristic of the agglomerations of chromite is the invariable association with them of globular (spherulitic) formations of prehnite, biotite, anhydrite, carbonate, zeolites, chlorite, talc, and occasionally, sulphides intergrown with these minerals. The globules are commonly confined to the central part of the agglomerations, and large agglomerations may contain several globules fairly uniformly distributed over the area. The globules have clearly defined boundaries and are composed of minerals that are not found in the rest of the agglomeration. Furthermore, chromite has never been found inside the globules, but their outer boundary is commonly fringed with chains of chromite grains. It is also important to note that in addition to the minerals with fugitive constituents,the globules may contain plagioclase and clinopyroxene. The grains of these phases extend as a rule from the agglomeration into the inner region of the globule, in the event of which the outer part of the globule abounds in chromite, while the portion of the crystal that is inside the globule, is devoid of it.

The disseminated chrome-spinellids, as well as the chromites found in agglomerations vary in optic and physical properties [41]. Their most important differences are, however, those of composition. Chromium-poor chromites develop in olivine gabbro-dolerites (Table 6, sample 22113[a]). The content of chromium in that spinel is 20% or less at a high concentration of titanium and at low contents of alumina and magnesium.

In picrite gabbro-dolerites we find dark spherical and light-coloured idiomorphic chromites markedly varying in composition (see Table 6). The former are rich in magnesium-alumina minerals and the latter in ferric oxide and titanium. Furthermore, the mafic chromites have the highest concentrations of chromium (31.9-38.6%), but are poor in titanium (2.0-3.5%). The atomic ratios Fe^{+3}/Fe^{+2} vary for the most part within the 0.5-0.8 range. The compositions of these chromites can be juxtaposed according to the diagram $Mg/Mg + Fe^{2+} - Fe^{3+}/Al + Cr + Fe^{3+}$ after [230]. In that diagram (see fig. 5) the area (field) representing chromites rich in magnesium and aluminum, is relatively small and is separated from all the other varieties.

The characteristic features of the light-coloured chromites are their low contents of chromium (19-26%) and alumina and their high concentrations of iron. It is highly significant that

these chromites are rich in the ulvöspinel component at contents of TiO_2 up to 12.5%. There have been recorded isolated grains with as much as 17% of TiO_2. These concentrations are among the highest of those quoted for chromites in the literature. Higher concentrations of TiO_2 have been recorded in lunar spinels displaying practically the complete compositional series from ulvöspinel to titanium-poor chromite, as well as p.32
in ultrabasic pipes, in which there have been identified chromites with as much as 20% of TiO_2. With regard to their TiO_2 concentrations the chromites described are comparable in composition to some of the chrome-spinels found in kimberlites [135] and to those from alkali-ultrabasic complexes [7]. All the other types of chromite ores, including the chromites found in alpinotype ultrabasic rocks, are usually poor in titanium.

The relationship between the increase in the concentration of titanium on the one hand and in the content of Fe^{+2} on the other is clearly observable in the chromites examined. In the diagram (fig. 5) these chromites are separated from the mafic chrome-spinellids and are displaced into the region of higher values of Fe^{+3} in the total of trivalent cations.

The variations in the composition of the chromite extend to a certain degree even into the chrome-containing magnetites associated with the chromites (see Table 6). Their concentrations of alumina and magnesium, respectively, are 2.0 and 1.8% or less. Their content of chromium remains fairly high, but varies within fairly large limits (2.0 to 15.8%). The magnetites may be differentiated into two groups on the basis of their titanium content: a titanium-rich group (8-10% Ti) and a group poor in titanium (2-3% Ti). No correlation has been observed between the variations in the content of titanium and other components of the magnetite. The compositions of the chromium-containing magnetites are located in the diagram (see fig. 5) on the extention of the variation line interconnecting the compositions of dark and light-coloured chrome-spinellids.

The chromites from the agglomerations resembling schlieren form a somewhat distinctive group from the viewpoint of their composition. The range of compositional variations in these chrome-spinellids is considerably smaller than that of disseminated chromites. It is characteristic that the variations in individual agglomerations are roughly the same. The most characteristic compositions which we borrowed from [41], and the results of new analyses published here for the first time, are presented in Table 7.

Comparison of all the analytical data shows that the chrome-spinellids found in agglomerations have the highest concentrations of chromium (36-44% Cr_3O_3) and that Fe^{+2} markedly predominates in them over Fe^{+3} ($Fe^{+2} : Fe^{+3} = 3:1$ or higher).

TABLE 6

Chemical compositions of spinellids from differentiated intrusions (weight %, X-ray microanalysis)

Oxides	1074	948-1	948-2	948-3	22113[a]	22056	22057-1	22057-2	22067	22094	T-6	T-7	T-4	T-14	T-15	H-257-1a	H-257-1b	H-1/73$_2$
TiO_2	2.2	0.3	0.3	0.14	8.3	2.7	1.9	2.3	3.6	0.03	2.5	1.9	3.6	12.5	9.1	2.2	11.5	8.10
Al_2O_3	54.3	55.8	54.4	58.8	5.6	15.6	18.8	17.3	15.0	61.20	15.7	20.0	15.0	6.1	5.1	16.8	5.3	None
Cr_2O_3	0.20	0.20	0.20	0.20	17.3	39.3	37.2	38.6	35.9	None	31.9	33.0	35.9	24.9	18.9	37.0	26.5	6.50
Fe_2O_3	4.50	7.2	8.9	3.3	31.2	10.1	10.5	10.5	10.86	9.60	17.6	15.1	10.7	15.4	27.5	10.5	13.2	45.0
FeO	27.2	29.4	29.3	30.8	37.0	24.4	20.2	22.06	31.1	8.50	22.2	19.0	27.9	38.4	38.2	26.3	37.7	36.10
MgO	9.7	7.8	7.7	7.1	2.3	8.2	10.5	9.6	6.10	19.70	9.1	11.7	6.1	3.9	1.9	6.5	3.3	1.00
MnO	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.20	0.17	0.36
NiO	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.10	0.20	0.40
Total	98.1	100.70	100.80	100.34	101.70	100.30	99.1	100.36	102.56	99.33	99.0	100.7	99.2	101.2	100.7	99.6	99.87	97.46

Number of cations

	1074	948-1	948-2	948-3	22113[a]	22056	22057-1	22057-2	22067	22094	T-6	T-7	T-4	T-14	T-15	H-257-1a	H-257-1b	H-1/73$_2$
Fe^{2+}	0.641	0.684	0.686	0.711	1.100	0.668	0.543	0.594	0.852	0.184	0.612	0.497	0.784	1.122	1.152	0.729	1.127	1.170
Mg	0.408	0.323	0.321	0.294	0.122	0.399	0.501	0.460	0.297	0.760	0.448	0.546	0.305	0.204	0.102	0.321	0.176	0.058
Fe^{3+}	0.094	0.152	0.187	0.070	0.835	0.248	0.254	0.255	0.268	0.187	0.436	0.356	0.271	0.405	0.745	0.261	0.408	1.315
Al	1.805	1.831	1.793	1.917	0.235	0.601	0.713	0.656	0.571	1.868	1.868	0.610	0.594	0.252	0.216	0.657	0.223	-
Ti	0.047	0.007	0.007	0.003	0.222	0.067	0.044	0.054	0.089	0.001	0.061	0.045	0.091	0.328	0.447	0.056	0.309	0.235
Cr	0.005	0.005	0.005	0.005	0.487	1.016	0.944	0.981	0.925	-	0.832	0.817	0.954	0.689	0.539	0.970	0.749	0.200
ΣR^{2+}	1.049	1.007	1.007	1.003	1.222	1.067	1.044	1.054	1.149	0.944	1.060	1.043	1.089	1.306	1.254	1.040	1.303	1.240
$\Sigma(R^{3+} + P^{4})$	1.951	1.995	1.992	1.995	1.779	1.932	1.955	1.946	1.853	2.056	1.940	1.956	1.910	1.647	1.747	1.950	1.693	1.750

(Table 6, continued)

Oxides	H-1/734	H-262$_2$	22741-1	22741-2a	22741-3	22741-4	22741-5	22741-6	22741-7	22741-8
TiO_2	10.2	2.80	4.3	4.3	2.7	2.1	4.3	4.4	3.9	1.8
Al_2O_3	None	1.50	9.8	9.0	15.3	14.3	10.4	10.2	11.4	16.6
Cr_2O_3	2.30	8.50	31.8	33.5	39.3	38.0	32.4	31.4	32.0	37.9
Fe_2O_3	45.3	52.2	19.00	18.13	10.78	13.73	19.32	28.51	18.21	12.54
FeO	38.3	31.5	30.39	30.32	24.00	23.57	28.6	21.12	29.17	21.48
MgO	0.8	1.2	4.4	4.4	8.6	8.1	5.9	5.0	5.2	9.5
MnO	0.50	0.2	-	-	-	-	-	-	-	-
NiO	0.32	-	-	-	-	-	-	-	-	-
Total	97.72	97.90	99.3	99.65	100.68	99.8	100.92	100.63	100.88	99.82
Number of cations										
Fe^{2+}	1.245	1.009	0.883	0.884	0.652	0.652	0.812	0.610	0.835	0.576
Mg	0.047	0.069	0.228	0.229	0.416	0.490	0.298	0.257	0.263	0.453
Fe^{3+}	1.325	1.507	0.497	0.475	0.264	0.342	0.494	0.741	0.469	0.303
Al	-	0.067	0.401	0.371	0.586	0.559	0.416	0.415	0.459	0.626
Ti	0.299	0.81	0.113	0.113	0.066	0.052	0.110	0.116	0.101	0.042
Cr	0.070	0.258	0.873	0.925	1.02	0.994	0.869	0.857	0.866	0.960
$\sum R^{2+}$	1.318	1.085	1.115	1.117	1.068	1.056	1.114	0.871	1.102	1.029
$\sum(R^{3+}+R^{4+})$	1.694	1.913	1.884	1.884	1.936	1.947	1.889	2.129	1.895	1.931

(Table 6, conclusion)

Oxides	22741-a	22741-b	22741-c	22741-d	22741-e	22741-f	22744-1	22744-2	22744-3	22744-4	22744-5
TiO_2	12.0	9.6	6.5	9.1	8.0	13.3	2.1	2.2	1.8	1.6	1.2
Al_2O_3	4.0	5.3	2.3	5.1	2.0	4.8	14.7	15.1	16.7	18.5	21.5
Cr_2O_3	18.9	19.60	23.5	18.9	20.1	19.7	35.77	33.6	37.2	36.6	35.3
Fe_2O_3	23.15	38.33	31.14	27.73	32.20	14.29	15.73	16.13	12.98	12.38	10.91
FeO	40.31	25.87	36.57	38.08	36.72	42.97	26.66	28.96	23.57	21.84	21.56
MgO	1.9	2.6	1.1	1.9	1.9	3.8	6.4	5.0	8.4	9.5	9.7
MnO	-	-	-	-	-	-	-	-	-	-	-
NiO	-	-	-	-	-	-	-	-	-	-	-
Total	100.26	101.30	101.11	100.98	100.92	98.86	101.29	100.99	100.65	100.42	100.17
						Number of cations					
Fe^{2+}	1.225	0.778	1.116	1.142	1.121	1.289	9.736	0.809	0.639	0.585	0.560
Mg	0.103	0.138	0.059	0.101	0.103	0.203	0.315	0.349	0.405	0.554	0.450
Fe^{3+}	0.633	1.037	0.855	0.748	0.884	0.386	0.391	0.406	0.318	0.298	0.256
Al	0.17	0.222	0.099	0.216	0.086	0.203	0.571	0.594	0.639	0.698	0.787
Ti	0.328	0.263	0.180	0.246	0.224	0.358	0.052	0.056	0.045	0.038	0.028
Cr	0.541	0.555	0.678	0.537	0.579	0.558	1.933	0.888	0.953	0.927	0.866
$\sum R^{2+}$	1.328	0.920	1.182	1.249	1.226	1.496	1.053	1.060	1.046	1.040	1.038
$\sum(R^{3+}+R^{4+})$	1.672	2.078	1.812	1.747	1.774	1.505	1.947	1.940	1.945	1.960	1.937

FOOTNOTE. Fully differentiated intrusions. The Talnakh intrusion: samples 1074, 948-1-3 --- hercynite from the altered olivine-containing gabbro-dolerite in the flange of the intrusion; sample 22113^a - titanium-rich chrome-spinellid from olivine gabbro-dolerite; sample 22057-T-4 --- magnesium- - and alumina-rich chromites from picrite gabbro-dolerites; T-14, 15 --- Titanium-rich chrome-spinellids from picrite gabbro-dolerites. The Noril'sk intrusion: H-257 --- H-262-2 --- chromites from picrite gabbro-dolerites. Differentiated leucocratic intrusions. The Manturovskii intrusion: 22741-1 --- 22741-8 --- magnesium- and alumina-rich chromites, and 22741a-22741f --- titanium-rich chrome-spinellids from picrite gabbro-dolerites; 22744-1 --- 22744-5 --- magnesium- and alumina-rich chromites from troctolites.

Fig. 5

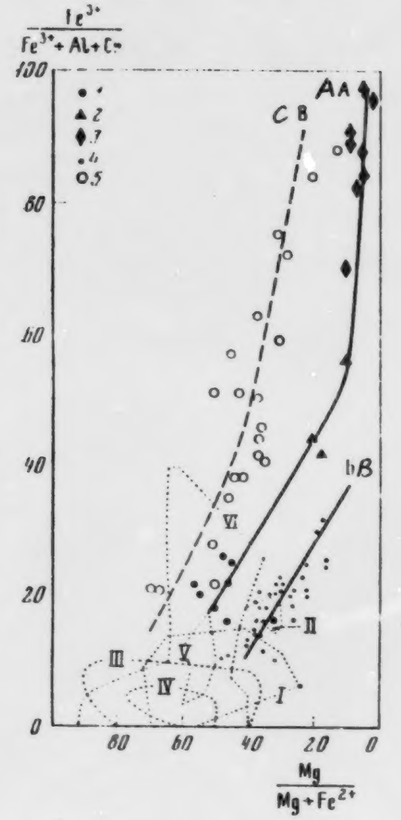

Diagram Mg(Mg+Fe^{+2}) - Fe^{+3} (Al+Cr+Fe^{+3}) for chromites from differentiated intrusions and other chromite minerals.

Differentiated intrusions from the Noril'sk region:
1,2 - disseminated chromites; 1-chromites enriched in magnesium and aluminum; 2-chromites enriched in ferric oxide and Ti; 3-Chromium magnetites; 4-Chromites from schlieren-like agglomerations; 5-The Gulinskii* pluton, accessory chromites and chromium magnetites from dunites and peridotites (after [7]).

Compositional fields of the chromites:
I-Stratified intrusions from Bushveld, Velikaya** dike and Stillwater (after [230]);

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* Transliteration. Translator.
** Velikaya=Great. Translator.

II-Muscox intrusion (after [230]);
III-Alpinotype ultrabasic rocks (after [230]);
IV-Intergrowths with polycrystalline diamond aggregates (after [135]);
V-Xenoliths of ulbrabasic rocks in kimberlite pipes (after [135]);
VI-Concentrates of kimberlite pipes (after [135]);
A,B,C-Lines showing variations in the composition of the chromites;
A-Disseminated chromites;
B-Chromites from schlieren-like agglomerations in the Noril'sk region;
C-Accessory chromites from the Gulinskii pluton.

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These distinctive aspects of composition account for the segregated position of the points representing these compositions in the diagram (see fig. 5). We could draw for these chrome-spinellids a variation line of their own that would run parallel to the variation line of the other chrome-spinellids without coinciding with it. We feel that the characteristic variations in the compositions of the two main morphological types of chromite ores are important indicators of genetic differences between them.

The boundary of the distribution of chromite is the contact zone of picrite and taxite gabbro-dolerites. No chromite has been encountered below that boundary, even though high concentrations of chromium persist in clinopyroxenes, as well as in the upper horizons of the intrusions. The spinel phase found in association with olivine is represented by the common green magnesium-alumina spinel (see Table 6, sample 22094). No chromium has been identified in the composition of the green spinel, but it contains substantial amounts of magnetite and hercynite minals. The general formula of the spinel is $(Mg_{0.76}Fe^{2+}_{0.18})_{0.94}(Al_{1.87}Fe^{3+}_{0.19})_{2.06}O_4$.

As was mentioned earlier, in the upper horizons of the intrusion there has been encountered a ferro-aluminous spinel close in composition to hercynite (see Table 6, samples 1074 and 948-1-3).

TABLE 7

Chemical compositions of the chromites from chromite agglomerations in picrite gabbro-dolerite (weight %, X-ray microanalysis)

Oxides	H-202-1	H-202-2	H-202-3	H-202-4	H-202-5	T-16-1	T-16-2	T-17-2	T-17-6	T-17-9	T-17-10	T-17-13	T-17-18	T-17-20	T-17-22	T-17-28
TiO_2	2.1	2.0	2.8	2.5	3.5	7.9	3.7	5.0	6.2	4.1	7.9	6.3	9.7	2.1	5.3	4.8
Al_2O_3	17.0	16.8	12.5	12.6	13.5	11.8	18.2	1[illegible].2	11.7	16.6	6.6	9.5	5.4	21.0	12.6	14.5
Cr_2O_3	41.7	42.4	44.3	44.3	41.5	35.3	37.1	36.5	37.5	36.4	34.7	38.5	33.7	35.6	37.9	35.8
Fe_2O_3	6.9	6.9	7.4	8.1	7.7	8.1	5.3	8.9	7.4	7.5	12.2	8.8	12.2	8.1	7.9	8.9
FeO	21.4	21.8	24.7	24.5	25.3	31.6	26.7	27.5	29.8	28.6	34.5	32.3	35.5	24.1	30.6	29.6
MgO	9.6	9.4	7.5	7.5	7.5	6.3	7.1	7.1	6.2	6.2	3.4	4.2	3.2	8.4	5.3	5.8
MnO	0.14	0.14	0.17	0.17	0.17	-	-	-	-	-	-	-	-	-	-	-
NiO	0.05	0.05	0.08	0.08	0.08	-	-	-	-	-	-	-	-	-	-	-
Total	98.89	99.49	99.45	99.75	99.65	101.0	98.4	99.2	98.8	99.4	99.2	99.6	99.7	99.3	99.6	99.4
Number of cations																
Fe^{2+}	0.583	0.591	0.694	0.686	0.708	0.885	0.741	0.771	0.850	0.794	1.028	0.939	1.042	0.648	0.871	0.834
Mg	0.466	0.454	0.375	0.374	0.374	0.314	0.351	0.354	0.316	0.307	0.180	0.217	0.219	0.402	0.268	0.291
Fe^{3+}	0.168	0.168	0.188	0.203	0.193	0.203	0.131	0.223	0.191	0.188	0.328	0.230	0.323	0.195	0.202	0.225
Al	0.654	0.642	0.494	0.497	0.533	0.467	0.711	0.561	0.160	0.651	0.276	0.988	0.224	0.797	0.505	0.575
Ti	0.051	0.049	0.071	0.062	0.089	0.199	0.092	0.127	0.471	0.102	0.212	0.165	0.255	0.050	0.135	0.121
Cr	1.074	1.087	1.175	1.173	1.099	0.934	0.972	0.966	1.010	0.956	0.979	1.058	0.935	0.905	1.020	0.953
$\sum R^{2+}$	1.055	1.051	1.075	1.066	1.088	1.199	1.092	1.125	1.166	1.101	1.208	1.156	1.261	1.050	1.139	1.125
$\sum (R^{3+}+R^{4+})$	1.947	1.946	1.928	1.935	1.914	1.803	1.906	1.877	1.832	1.897	1.795	1.841	1.737	1.947	1.862	1.874

FOOTNOTE. The table shows typical compositions of the chrome-spinellids forming chromite agglomerations in picrite gabbro-dolerites from the Noril'sk (samples H-202-1 to H-205-5) and Talnakh (samples T-16-1 to T-17-28) intrusions.

The proportion of the spinel and hercynite minals in the composition of that spinel is close to 0.35Sp 0.7Hr and there are practically no other minor components.

It is thus evident that cryptic layering is also well pronounced in the composition of spinellids. The compositional variations of spinels are, however, much more complex than those of olivine or pyroxene, which is due to the distinctive nature of the process resulting in the crystallization of spinel from magmatic melts.

Differentiated leucocratic intrusions. The main characteristics of differentiated leucocratic intrusions distinguishing them from fully differentiated intrusions are as follows: 1) Basic rocks predominate in the composition of differentiated leucocratic intrusions, and ultrabasic rocks merely form isolated irregularly shaped bodies amidst olivine-rich differentiates; 2) Ultrabasic and olivine-rich gabbro-dolerites from these intrusions contain very small quantities of disseminated sulphides; the largest concentrations of such sulphides have been recorded in the horizon of taxitic gabbro-dolerites; and 3) These intrusions have a lower total content of sulphides. Otherwise the stratification and cryptic layering are similar in these two types of differentiated intrusions (see fig. 3).

Acid differentiates all the way to amphibole granites and granodiorites are the characteristic rocks in the upper horizons of these intrusions. Gabbros, gabbro-diorites and olivine-free gabbro-dolerites are found in the underlying horizons. Olivine-containing and olivine gabbro-dolerites have the greatest thicknesses. The main changes in the mineral composition and texture of these rocks are the increased contents of olivine and clinopyroxene, reduced grain size, and replacement of hypidiomorphic, gabbroid and panautomorphic-granular textures by ophitic or poikilophitic textures. Rock varieties which may be referred to as picrites or troctolites, have been identified among the rocks in the horizon of olivine gabbro-dolerites, particularly in its bottom part. On the other hand no varieties of rocks corresponding to plagioperidotites or olivinites have been encountered in that horizon. Picrites and troctolites themselves are interbedded with equigranular or ataxic olivine gabbro-dolerites.

Large-grained equigranular or, less often, taxitic gabbro-dolerites occur below that horizon, and contact gabbro-dolerites close the section.

Characteristic features of cryptic layering in differentiated leucocratic intrusions are shown in fig. 3. We wish to note that the range of variations in the composition of the essential rock-forming minerals is considerably smaller in the intrusions discussed than in fully differentiated intrusions. The composition of olivine is up to Fo_{82} in picrites and troctolites, Fo_{75} in olivine gabbro-dolerites and up to Fo_{65} in taxitic gabbro-dolerites. The concentration of iron in the inner regions of zoned clinopyroxene crystals varies from the minimal p.35 values of $f_{at}=0.16$ that are characteristic of picrites, to $f_{at}=0.3$ in the upper horizons and $f=_{at}=0.2 - 0.25$ in the bottom differentiates of the intrusions. The variations in the composition of orthopyroxene and plagioclase follow the same pattern.

As was mentioned earlier, chromium-containing spinels have been identified among the constituents of differentiated leucocratic intrusions, but are present there in considerably smaller quantities than in fully differentiated intrusions. Chromite is found in these intrusions only in the form of sparsely disseminated grains, but forms no large agglomerations of the kind that is characteristic of fully differentiated intrusions. Chromite occurs as a rule in the form of inclusions in plagioclase or, considerably less often, in clinopyroxene.

Contrary to what has been observed in fully differentiated intrusions, in the massifs described light-coloured chromites are much more widely distributed than mafic chromites.

The two morphological varieties of chrome-spinellids markedly differ in composition (see Table 6, samples 22741 and 22744). Dark-coloured chromites are rich in chromium (32-39%

Cr_2O_3), alumina (10-21% Al_2O_3) and magnesium (5-9%) MgO). Light chromites are very rich in titanium (7-14% TiO_2) and have an increased content of Fe^{3+}, but are very poor in alumina and magnesium, and contain considerably less chromium (18-23% Cr_2O_3). As was mentioned earlier, titanium chromites quantitatively predominate over the chromes spinellids poor in titanium. This is one of the major differences between the differentiated leucocratic intrusions and fully differentiated massifs.

Differentiated melanocratic intrusions. The third type of differentiated sulphide-bearing intrusions is less well known in the literature than the others and is therefore examined here in greater detail. The main characteristic of these intrusions is the predominance in their composition of ultrabasic differentiates, mainly of troctolites and, to a lesser degree, of picrites. Intrusive masses of this type may be referred to as differentiated melanocratic intrusions. This group includes the Nizhne-Talnakh, Nizhne-Noril'sk, Burkanskii, Zelenaya Griva, Klyukvennyi and a number of other intrusions. A diagrammatic representation of the structure of one of the massifs is shown in fig. 3. The characteristic succession of horizons in the vertical section of these intrusions is as follows.

The horizon of acid leucocratic rocks ranges in composition from quartz diorites to granodiorites and attains its greatest thicknesses in the swells of the intrusions. The rocks have a large-grained aspect and a hypidiomorphic texture.

The horizon of gabbro-diorites and gabbros is a typical horizon of these intrusions. It is composed of large- and medium-grained panautomorphic-granular or, less often, gabbro-ophitic rocks.

The horizon of olivine-free, olivine-containing and olivine gabbro-dolerites has been recorded at all the intersections of the intrusions. Unlike the first two horizons of differentiated intrusions this one commonly has a small thickness. Its constituent rocks are uniformly medium-grained, panautomorphic-granular in the upper part of the horizon and ophitic in its bottom portion. It has been observed that the granularity of the rocks decreases somewhat in the lower part of the horizon.

The rocks of the three horizons described above constitute as a rule a minor portion of the section in the intrusions, a quarter or less of the total thickness of the intrusive bodies.

The horizon of troctolites and picrites. This horizon represents the major portion of the intrusion volume. It commonly has a monotonous fine- to medium-grained texture with rare relatively small schlieren-like loci of more markedly leucocratic large-grained rocks. The transition from the rocks of the superjacent horizons is relatively sharp and is fixed by the degree of alteration of the texture and by the quantity of mafic minerals, mainly olivine. Ophitic textures are less characteristic of constituent minerals from the ultrabasic horizon of the type of intrusions described than of those from fully p.36
differentiated intrusions, but on the other hand panidiomorphic and allotyiomorphic textures are more common in this horizon.

The horizon of contact gabbro-dolerites is composed, as a rule, of fine-grained ophitic, less often porphyritic rocks.

In contrast to fully differentiated massifs, in differentiated melanocratic intrusions the alterations in the composition of their rock-forming minerals are unidirectional. The leading association of the ultrabasic horizon is Ol^{30-50} + Pl^{30-50} + Kpx^{10-20} + Opx^{5}. Variations in the ratios of Ol, Pl and Kpx determine whether the rocks are classified as troctolites or as picrites. Orthopyroxene has a limited development in this horizon; subcalcium augite is present. The characteristic mineral of the horizon is biotite. It is important to stress that in contrast to picrites from the fully differentiated massifs, these rocks contain no chrome spinellids. The accessory minerals encountered here are magnetite and ilmenite.

Olivine and olivine-containing gabbro-dolerites contain the mineral association Pl^{45-60} + Kpx^{20-30} + Ol^{5-15}; gabbros and gabbro-diorites Pl^{50-60} + Kpx^{20-25} + Ro^{5-10} + Q^{1-3} Mk^{1-3}; diorites and granodiorites $Pl^{40-60} + Ro^{10-20} + Q^{5-15}$. The lower contact gabbro-dolerites $Pl^{40-50} + Kpx^{20-40} + Ol^{15-20}$.

Cryptic layering of differentiated melanocratic massifs (see Tables 3 and 4 and fig. 3) differs markedly from that of the two other types of stratigraphic intrusions. The main difference is that the composition of the constituent minerals remains constant throughout most of the vertical section in these massifs.

Olivine. The composition of olivine Fo_{81-87} remains the same from the point where it appears in olivine and olivine-containing gabbro-dolerites to the lower contact of the massif, except for the endocontact facies, where olivines with somewhat lower magnesium concentrations (to Fo_{75}) occur alongside Fo_{79}.

Clinopyroxene is represented by augite. Its composition remains constant throughout most of the section in the intrusion. The inner zones of the clinopyroxene crystals have a strictly constant content of iron F_{at}=0.18 and are composed of Kpx with f_{at}=0.23 only in the contact zone of the massif.

The concentration of iron increases very little in the outer zones of the crystals and does not exceed there f_{at}=0.21. Minor variations have been observed in the contents of alumina and titanium.

Subcalcium augite is a characteristic mineral of this type of intrusions and it occurs throughout the section of the intrusions. This mineral forms discrete grains crystallized in the rock in the same textural position as common Kpx.

Orthopyroxene is found extremely rarely in these massifs. Compared to Opx from the other massifs, it has here the highest magnesium concentration (f_{at}=0.25) and does not vary in composition in different parts of the picrite-troctolite horizon.

As may be seen from the data presented above, cryptic layering follows a well-defined pattern in differentiated intrusions. This pattern is fairly similar in fully differentiated and differentiated leucocratic intrusions, but is substantially different in differentiated melanocratic intrusions. Crystallization of the melt in the former is accompanied by a continuous alteration of the composition and an extensive interaction of the early solid-phase products with the residual liquid during the gravitational segregation of crystals; moreover, the parameters characterizing the state of the melt vary markedly in different parts of the magma column.

The data obtained in the course of this study do not support the conclusions drawn in the work [48] regarding the evening up of the parameters of state and composition of the melt by the time of its injection into the hypabyssal chamber. On the contrary, it appears to be preceded by a substantial differentiation of the melt into layers during the ascent of the magma. However, judging from the degree and thoroughness of fractionation of the high-temperature phases, the number of crystals in the melt was small prior to its injection, and mass crystallization corresponds in time to the localization of the melt in the hypabyssal chamber. The factors controlling the crystallization processes of magmatic melts in differentiated melanocratic intrusions are fundamentally different. These massifs p.37 crystallize at relatively uniform parameters of the composition and state of the melt. The key factor in the formation of the layering is gravitational segregation of the protocrystals forming prior to the intrusion of the melt into the hypabyssal chamber. Differences of this kind are due to the varying contents of the fluid phase in the magmas.

THE MAIN STRUCTURAL CHARACTERISTICS OF THE ORE FIELDS AND DEPOSITS FROM THE NORIL'SK PROVINCE

The ore fields found in the province of Noril'sk are regular associations of intrusive rocks and copper-nickel sulphide ores confined to intrusive formations. The distribution of the ore fields within the framework of the territory examined is controlled by the tectonic conditions in the peripheral parts of the trap depressions, by the position of deep-seated faults and by the development of crustal upthrow-fault dislocations (see fig. 1).

All these principal structural components have been identified in the major ore fields. They include the brachysynclines and brachyanticlines developed in the periphery of the depressions and adjoining elevations; the zones of deep-seated faults detected, as was shown earlier, by a number of features; and the young tectonic disturbances determining the morphology of the intrusive bodies and the intensive postmineral tectonics.

The ore fields are composed of different types of differentiated massifs. Most of them are large apophyses of intrica(te)ly structured intrusive massifs branching off at the front of the intrusion of the platform mantle into their upper horizons. Most of the massifs are closely spaced and are interconnected by relatively thin sills. Some of the massifs appear to have no direct links with analogous magmatic bodies. Massifs of this kind are located at a considerable distance from one another and the only connection between them seems to be the common magmatic source from which they originated. A highly characteristic feature is the concurrent development of fully differentiated and differentiated melanocratic intrusions in the ore fields. The horizons in which the intrusions and the associated sulphide ores are localized may be composed of any of the rocks constituting the platform mantle.

Sulphide ores concentrate within the intrusive massifs and in sedimentary-metamorphic, volcanic or, less often, intrusive rocks of the exocontact in the massifs.

The main ore fields of the Noril'sk region are the Talnakh, Noril'sk and Imagdinskii fields.

Since the geological factors controlling the distribution of these fields are the same, the fields are fairly similar in structure. We shall therefore focus on the Talnakh ore field and only briefly analyze the structural characteristics of the other ore fields.

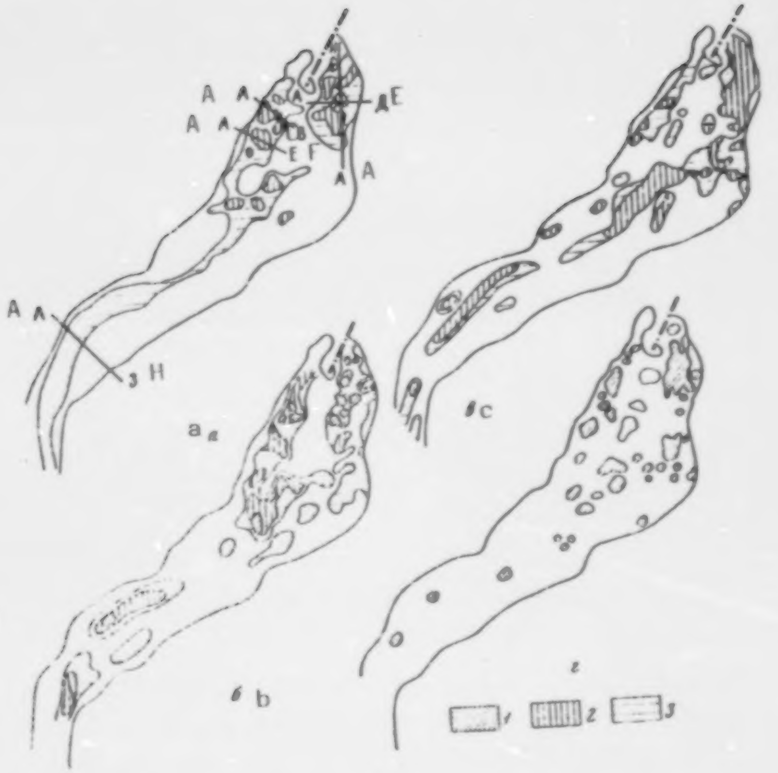
The Noril'sk ore field

The geological structure of the deposits found in the Noril'sk ore field of differentiated intrusions and of the ores associated with these deposits has been studied at different times by N.N. Urvantsev, V.K. Kotul'skii, M.N. Godlevskii, G.B. Rogover, I.A. Korovyakov, V.S. Domarev, M.F. Smirnov, G.D. Maslov, E.N. Sukhanova, V.F. Kravtsov, Yu.N. Sedykh, L.L. Vaulin, M.K. Ivanov, V.V. Zolotukhin, A.D. Genkin, L.A. Vinnitskii, V.A. Lyul'ko, A.V. Tarasov and many other researchers.

The Noril'sk ore field comprises several deposits grouped within a relatively narrow area at the northern centroclinal closure of the Noril'sk trap depression. The deposits are confined to differentiated intrusive massifs, among which the most important ones are the Noril'sk I and Noril'sk II intrusions, the Zubovskii, Chernogorskii and certain other smaller intrusions.

The deposit Noril'sk I is confined to the differentiated intrusion bearing that name. The horizon in which the intrusion is localized, is composed of terrigenous-carboniferous sedimentary rocks of the Permo-Carboniferous age (the Tunguska sequence) and of extrusive traps. The massif stretches in the northeastern direction and gently plunges southwest with a small unconformity relative to the stratification of volcanic and sedimentary rocks. As a result of this the northern parts of the intrusions are localized entirely in extrusive rocks in-between the sheets of tholeiite and labrador basalts of the Syverminskii suite. In the south the massif is overlain by two-feldspar basalts, but is rooted with its base in terrigenous-carboniferous rocks. p.39

Fig. 6



Distribution of disseminated ores in horizons of picrite (a) and taxite (b) gabbro-dolerites, of veinlet-impregnated* (c) and massive (d) ores at the exocontact of the Noril'sk I intrusion [134].

1-3---Relative gradations of sulphide contents (denser hatching corresponds to increases in the concentration of sulphides).

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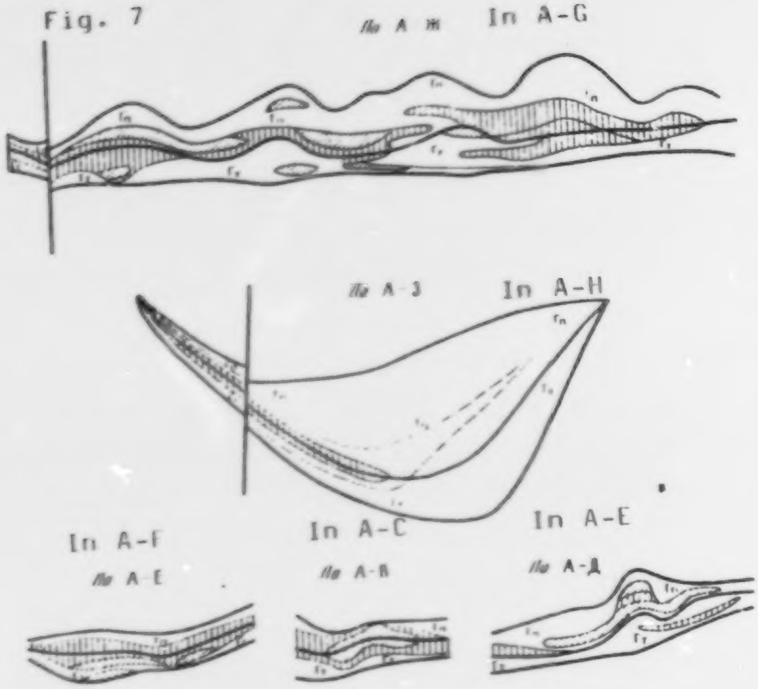
* disseminated? Translator.

Fig. 7



Distribution of ores in the horizons of impregnated ores at the Noril'sk I intrusion. See legend to fig. 6.

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In its southern and central parts the massif is an integral body in the form of a chonolith complicated by local downwarps at the base of the intrusion. The roof of the massif has virtually no perceptible undulations. In the north the massif is split into two large (western and eastern) branches interconnected by a relatively thin sill. According to the data of G.D. Maslov [78], in the flanges of each of these branches there develop subtabular steeply dipping apophyses. The characteristic aspects of the relationship between the intrusion and other age groups of intrusive rocks are as follows: 1) Differentiated intrusions break through the sills of titanaugite and poikilophitic olivine-containing dolerites occurring in Permo-Carboniferous deposits (see fig. 6): 2) No direct contacts with differentiated melanocratic (Nizhne-Noril'sk and Morongovskii) intrusions have been observed. These intrusions are exposed south of the deposit, where they occur amidst basaltic sheets of the Morongovskii suite. The same intrusions have been detected by drilling in Devonian deposits.

The most important structures controlling the localization of the Noril'sk differentiated intrusion are the strike-shift fault of a northeastern trend, which forms the southern part of the Noril'sk-Kharaelakhskii fault [112,97,78, and 142], and the submeridional tectonic zones [78 and 142]. The conjunction of these disturbances accounts for the distinctive shape of the intrusion and for its division into branches. It is characteristic that the locales with the greatest thicknesses of the intrusive bodies are stretched in the direction of the main tectonic disturbances. The tectonic zones mentioned above played an important part in shaping the deposits into what they are now. Post-intrusive movements along these disturbances account for the block structure of the deposit. Individual displacements measure up to tens of metres.

Copper-nickel sulphide ores are represented in the deposit by several morphological types and occur within the intrusion, as well as in the underlying rocks of the exocontact. The structure of the ore zone and the distribution of sulphide-rich locales within that zone are shown in the plans of individual horizons (fig. 6). The largest concentrations of the ores are confined to the flanges of the intrusion. Mineral concentrations are found here in picrite and taxite gabbro-dolerites; impregnated ores have the greatest areal extent in the labrador basalts and titanaugite dolerites underlying the intrusion; massive sulphide ores are also present. It is interesting to note that the ore concentration maxima show a fairly good coincidence in different horizons of the ore zone. The intensity of mineralization decreases markedly down the dip of the massif. In picrite gabbro-dolerites (figs 6 and 7) the part of the horizon enriched in sulphides forms a continuous strip that stretches down the dip of the intrusion and is located asymmetrically relative to the axial line of the massif. In the centre of the intrusion p.40 the width of its mineralized part is minimal, because of a large projection in the relief of the underlying rocks in that area. In taxitic gabbro-dolerites the locales enriched in sulphides are in the form of isolated spots stretched down the dip of the intrusion (figs 6 and 7). The distribution of ores in the vertical sections of picrite and taxite gabbro-dolerites is shown in general lines in fig. 7.

The concentration of impregnated ores in the rocks underlying the intrusion also decreases perceptibly down the dip of the massif (see fig. 6). The continuous ore zones in the flanges give way to smaller isolated areas coinciding in outlines with the locales of sulphide-rich taxite gabbro-dolerites. Similar features have been observed in the distribution of massive ores (fig. 6).

The Chernogorskii deposit is confined (see fig. 6) to the Chernogorskii intrusion stretching in the sublatitudinal direction. The west-north-west angle of dip of the intrusion is 8-10°. The horizon in which the massif is localized is at the boundary of terrigenous-carboniferous Permo-Carboniferous deposits on the one hand and carbonate rocks of the Devonian age on the other. The intrusion is similar to a chonolith in the outline of its transverse section and is tabular in the vertical section. Unlike the intrusion Noril'sk I, the Chernogorskii intrusion has a steeper dip in its western part, as a result of which the stratigraphic level of its base drops 300-400m over a relatively small distance.

In the flanges of the intrusion there have been observed fairly numerous tabular apophyses intersecting both terrigenous-carboniferous deposits and lava sheets. Some of the apophyses crop out on the surface in the form of low-angle dikes varying in thickness.

The attitude and structure of the intrusion are controlled by submeridional tectonic zones which may be related to the large-scale upthrow faults located west of the intrusive massif.

Copper-nickel sulphide ores are distributed concordantly with the extension of the intrusive massif. As has also been observed in the Noril'sk I deposit, the highest ore concentration is found here in the eastern flange of the intrusion. Impregnated ores occur in picrite and taxite gabbro-dolerites, as well as in the carbonate rocks underlying the intrusion. Massive ores are found in the form of relatively thin veins or veinlets. Down the dip of the intrusion sulphide-rich locales gravitate towards the axial part of the massif, but in picrite and taxite gabbro-dolerites the lateral extent of the enriched zone is considerably smaller. In these areas ores are found only sporadically in the rocks underlying the intrusion. Down the dip of the Chernogorskii intrusive massif the ore zone thus generally decreases in thickness and its structure grows much simpler, as is also the case at the Noril'sk I deposit.

The Noril'sk II deposit. The main distinctive feature of the Noril'sk II deposit is that the intrusive massif, to which the mineral concentrations are confined, is a steeply dipping body of a highly complex structure. Thick dike-like apophyses are extensively developed in the roof of the intrusion. The main body of the intrusive massif dips at the base at sharply varying angles ranging from 10-15° to 50-70°. In different parts of the massif its base dips towards the centre, as a result of which the bowl-shaped body changes in deep-seated horizons to a dike-like formation, which may pinch out with depth. This complex morphology of the massif is due to the presence in the area, where the intrusion is localized, of numerous tectonic disturbances varying in strike.

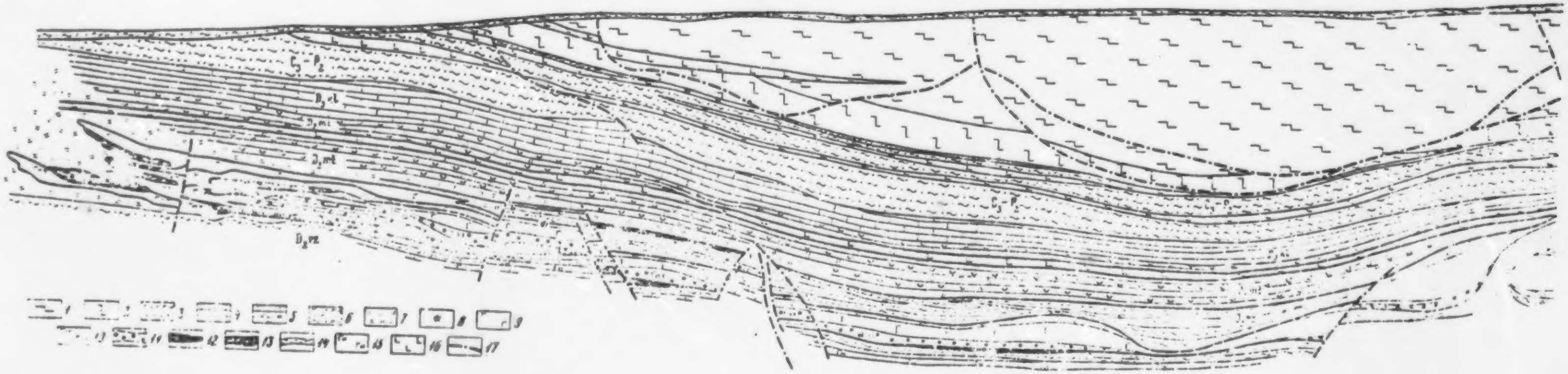
Sulphide mineral concentrations are found in the deposit mainly in the form of impregnated ores in the lower differentiates of the intrusion represented by troctolites, picrite and taxite gabbro-dolerites. Other types of mineral concentrations are not characteristic of the deposit discussed.

Fig. 8

Fig. 8

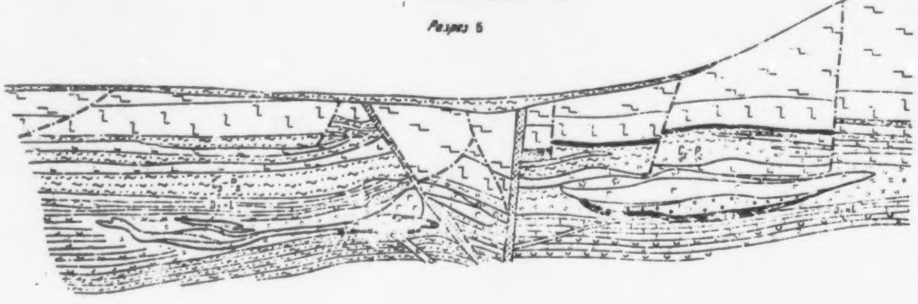
Section A

Разрез А



Section B

Разрез Б



Фиг. 8. Схематические геологические разрезы Северо-Западной части Талнахского рудного поля (по данным НКГРЭ с дополнениями авторов)

1 — толеитовые базальты, сыверминская свита P_2T_1sv;
2 — двуполевошпатовые, лабрадоровые и титан-авгитовые базальты, ивакинская свита P_2iv;
3 — песчаники, алевролиты, аргиллиты, углистые аргиллиты, угли, тунгусская серия C_2-P_2;
4 — доломиты, известняки, каларгонская свита D_3kl;
5 — ангидриты, мергели, мантуровская свита D_2mt;
6 — аргиллиты, разведочнинская серия $D_{1-2}rz$;
7 — контактово-метаморфические и метасоматические породы;
8 — диориты, габбро-диориты, габбро;
9 — габбро-долериты, безоливиновые, оливинсодержащие, оливиновые;
10 — габбро-долериты пикритовые и такситовые;
11 — 14 — руды:
11 — вкрапленные в интрузивных породах,
12 — [illegible],
13 — [illegible],
14 — [illegible];
15 — силлы [illegible] габбро-долеритов;
16 — [illegible];
17 — [illegible]

(Fig. 8, continued)

Diagrammatic representations of geological sections from the northwestern part of the Talnakh ore field (according to the data of NKGRE* supplemented by the authors)

1-Tholeiite basalts of the Syverminskii suite P_2T_1sv;
2-Two-feldspar, labrador and titanaugite basalts of the Ivakinskii suite P_2iv;
3-Sandstones, siltstones, argillites, carbonaceous argillites and coals of the Tunguska series C_3-P_2;
4-Dolomites and limestones of the Kalargonskii suite D_3kl;
5-Anhydrites and marls of the Manturovskii suite D_2mt;
6-Argillites of the Razvedochninskii suite $D_{1-2}rz$;
7-Contact metamorphic and metasomatic rocks;
8-Diorites, gabbro-diorites and gabbros;
9-Olivine-free, olivine-containing and olivine gabbro-dolerites;
10-Picrite and taxite gabbro-dolerites;
11-14---Ores;
11-Impregnated in intrusive rocks;
12-Massive;
13-Breccioid;
14-Veinlet-impregnated;
15-Sills of undifferentiated gabbro-dolerites;
16-Titanaugite dolerites;
17-Tectonic disturbances.

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The Talnakh ore field

p.41

Geological structure

The Talnakh ore field comprises two (Talnakh and Okryabr'skii) spatially close deposits [8 and 69], both of which are confined to differentiated intrusive massifs combined under the name of the Talnakh intrusion. The Talnakh ore field displays many typical features of the copper-nickel deposits from the Noril'sk region. The discovery and subsequent detailed studies of the Talnakh deposits opened up new ways for solving general problems of mineralogy, geochemistry and genesis of copper-nickel ores. The main progress in these areas has been achieved as a result of the studies carried out bv V.F. Kravtsov, Yu.N. Sedykh, E.N. Sukhanova, V.S. Nesterovskii, L.L. Vaulin, N.I. Korgun, V.E. Kupilov, D.A. Dodin, V.N. Batuev, V.M. Isoitko, A.D. Genkin, V.V. Distler, A.A. Filimonova, N.N. Shishkin, G.I. Mitenkov, V.V. Zolotukhin, V.V. Ryabov, V.V. Yudin, D.B. Turovtsev, Yu.K. Krakovetskii and a number of other researchers. Highly important data have been obtained after the exploitation of the deposits began. These data significantly added to the information collected in the process of drilling.

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* Transliteration. Translator.

The stratigraphic column of the Talnakh ore field is typical of the Noril'sk region. The section is composed of sedimentary complexes ranging in age from Silurian to Permian, and of Lower Triassic extrusive traps. The youngest extrusive formations are the basalt sheets of the Mokulaevskii suite.

The Talnakh ore field is localized in the periphery of the Kharaelakhskii trap depression, in the area of its southern centroclinal closure. The zone where the negative structure (i.e. the Kharaelakhskii depression) changes to the ridge-like elevation known as the Khantaiskii-Rybninskii ridge, resembles a flexure and is one of the main factors responsible for the present-day tectonic position of the Talnakh ore field [101 and 102]. The fairly large tectonic zone of the Noril'sk-Kharaelakhskii fault is the principal structural element in the ore field. Within the confines of the Talnakh and Oktyabr'skii deposits this tectonic zone has manifested itself in a number of premineral and postmineral strike-shift dislocations accounting for the rather complex present-day structure of the ore field as a whole and for the distinctive magmatism and morphology of the intrusive massifs.

The zone of the Noril'sk-Kharaelakhskii fault divides the territory of the Talnakh ore field into the Eastern and Western parts differing markedly in tectonic structure (see fig. 2). The eastern half is a monocline complicated by a limited number of faults running parallel to the main fault zone. The western half is characterized by intensive tectonic disturbances and wide-spread plication phenomena and disjunctive dislocations.

The main zone of the Noril'sk-Kharaelakhskii fault is a graben-like structure comprising a number of subparallel sutures (geofractures) with angles of dip varying from 40 to 85°. The eastern fault referred to as the Glavnyi* suture, is the steepest one. The set of disturbances located west of the Glavnyi suture (the system of western faults) has lower angles of dip. The amplitudes of the displacements along the tectonic zones vary from 50 to 400m.

The most important structural characteristic of the western part of the ore field is the specific effect of tectonic deformations in the horizons of basalts and sedimentary rocks [101 and 102]. In extrusive rocks the main tectonic deformations are in the form of block displacements along the fissures shaped like curved surfaces. Within the blocks the sheets are commonly stratified in a subparallel fashion, but neighbouring blocks may be arranged at fairly large angles in relation to one another. p.42

A very interesting tectonic characteristic of the lava horizon is that the faults bounding the blocks fairly rapidly die out upon reaching the underlying sedimentary rocks. Only some of them have been traced in the terrigenous-carbonaceous Permo-Carboniferous sediments and none have been found in the carbonate-sulphate deposits of the Devonian age. These rocks have their own system of disturbances, which also do not extend into the rocks of the superjacent horizons.

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* Glavnyi = main, chief, principal. Translator.

The tectonic elements examined appear to be interlinked by the common time of formation. The inception of these structures antedates the injection of differentiated intrusions, since tectonic characteristics of different parts of the ore field are distinctly reflected in the structure of the respective intrusive massifs located therein. Further development of these structures appears to correspond in time to the migration of magma. V.F. Kravtsov, Yu.N. Sedykh [102] and other researchers relate, for example, the block structure of the extrusive horizon to the phenomena of subsidence associated with the injection of intrusions. Movements along these disturbances undoubtedly occurred in the post-intrusive time too. This is evident from the record of many displacements of isolated parts of the intrusions and of the copper-nickel ores conjugated with them.

Within the boundaries of the ore field trap intrusions are represented by undifferentiated sulphide-free sills of poikilophitic titanaugite dolerites, and stratified sulphide-bearing intrusions by the fully differentiated Talnakh massif and by the differentiated melanocratic Nizhne-Talnakh massif.

The Nizhne-Talnakh intrusion is a complex body stretched in the submeridional direction. The most characteristic feature of its morphology is the presence of large isometric swells disturbing here and there the generally tabular shape of the intrusion. In these locales the intrusion is pipe-like in appearance. In tectonic plan the pipe-like swells develop mainly in the flexure-like structures adjoining the Noril'sk-Kharaelakhskii fault [74]. In the other parts of the ore field, particularly west of the fault, the intrusion changes to a sheet-like deposit traced for several tens of kilometres.

An important feature of the intrusion is the presence of several dike-like gently dipping apophyses at a number of loci in its roof. The apophyses diverge towards the Verkhne*-Talnakh intrusion. It has been established beyond doubt that some of these apophyses connect with the Verkhne-Talnakh intrusion.

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* Verkhne = Upper. Translator.

Internal structural characteristics of the massif are related to its morphology. The most extensively developed differentiates in the tabular locales of the massif are olivine gabbro-dolerites that are succeeded in the bottom part of the intrusion by troctolites with small locales of picrites.

In the swells of the intrusions their stratification patterns are more regular. According to the data of D.A. Dodin [64], the differentiates identified in the intrusion are as follows: 1) Contaminated rocks and contact gabbro-dolerites (0-55m in thickness); 2) Diorites, metadiorites (up to 75m in thickness); 3) Olivine-free and olivine-containing gabbro-dolerites (up to 40m in thickness); 4) Olivine gabbro-dolerites (5-45m) and troctolite gabbro-dolerites (5-40m); 6) Picrite gabbro-dolerites (10-50m); 7) Taxite gabbro-dolerites (0-30m); and 8) Contact gabbro-dolerites (0-5m). The lower differentiates of the intrusion commonly contain impregnated sulphides. A characteristic feature of the rocks in the Nizhne-Talnakh intrusion is the porphyritic aspect of its most widely distributed differentiates, such as olivine or troctolite gabbro-dolerites. Porphyritic rocks occur in the sheet-like (tabular) part of the intrusion and compose the low-angle dikes linking the Verkhne-Talnakh and Nizhne-Talnakh intrusions.

The Nizhne-Talnakh intrusion displays fairly small (3-5m or smaller) aureoles of metamorphic and metasomatic alteration products. p.43

The fully differentiated Talnakh intrusion unites several intrusive bodies. The spatial position and morphology of these bodies are distinctly related to the tectonic structure of the locales in which they are emplaced.

The intrusive branch located east of the main disjunctive structure in the Talnakh ore field, is localized amidst Permo-Carboniferous (the Tunguska series) terrigenous-carbonaceous rocks. The massif is gently tilted in the submeridional direction. The central part of the massif is most markedly downwarped in stratigraphic plan. In that locale the base of the massif partly extends into the Upper Devonian limestones of the Kalargonskii* suite. North and south the massif rises stratigraphically and its roof moves close to the contact of terrigenous beds with extrusive rocks. The massif has a relatively simple morphology. In the longitudinal direction it is tabular and varies little in thickness. In transverse section the massif is close to a chonolith in shape. Splitting up of the intrusive body in the flanges is not characteristic of this massif. From the viewpoint of its structure the Eastern massif has many features in common with intrusions of the Noril'sk ore field.

The next branch of the Talnakh intrusion is localized in the zone of the graben-like structure formed by the Noril'sk-Kharaelakhskii fault. The original shape of the intrusion has been obscured to a large extent by the postintrusive tectonic movements. However, if we disregard the late deformations, its morphology appears to be similar to that of the intrusive body located in the Eastern part of the ore field. This intrusion is localized in the same stratigraphic horizon, is also tabular in shape along the strike and chonolith-like in transverse section. The massif has been traced for a limited distance and pinches out in the north near the Glavnyi suture (geofracture) of the Noril'sk-Kharaelakhskii fault. The evidence available thus far is inadequate for determining precisely the forms of relationship between these two intrusive bodies.

The intrusive branch from the western part of the ore field differs markedly from the two massifs examined above because of its large size and highly intricate internal structure. The complexity of the tectonic structure in the Western locale is distinctly related to the morphology of the massif. V.F. Kravtsov [101 and 102] has demonstrated that the elongation of individual apophyses of the massif and the variations in their thicknesses are concordant with the position of the major blocks in the ore field.

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* Transliteration. Translator.

The general submeridional plunge of the branch discussed is close to the dip of the rocks in the rim of the trap depression. In addition to that different parts of the massif tend to dip in a centroclinal fashion, as a result of which the most stratigraphically downwarped part of the body is in the centre, while its marginal parts are stratigraphically raised. The latter is clearly observable in sections (fig. 8). The downwarped part of the massif encloses dike-like bodies linking the massif with the Nizhne-Talnakh intrusion.

In longitudinal section the generally tabular shape of the massif is complicated by numerous swells and pinches, the position of which is often concordant with the morphology of plicated dislocations in the country rocks. In transverse section the shape of the massif resembles a chonolith.

The intrusion is localized in Lower and Middle Devonian rocks. The massif generally dips in such a manner that the intrusion occurs in different horizons of the Lower-Middle Devonian stratigraphic section. In its peripheral the massif is enclosed in Middle Devonian rocks of the Manturovskii suite, while its isolated apophyses may reach the horizon of the Upper Devonian Kalargonskii suite. In the most markedly downwarped part of the intrusion the lower contact drops to the level of the Lower Devonian Kureiskii suite.

The intrusive bodies localized in sulphate-carbonate sediments, have an intricate structure on account of their separation into a series of subparallel apophyses varying in thickness. The flange of the Western massif has a particularly complex structure. The section of that flange is composed of intrusive rocks repeatedly alternating with interlayers of sedimentary-metamorphic varieties. The shape of the apophyses is so unstable that it is often impossible to tie their fragments together into integral bodies. Some of the agglomerations of magmatic rocks appear to be isolated lenticular bodies. p.44

Depending on the thickness of the apophyses, their constituent rocks may be represented by holocrystalline or finely crystalline and vitreous varieties. The latter are characteristic of bodies with a small thickness. The degree of differentiation of the apophyses is also related to their thickness. As a rule, the bodies measuring a few metres or less in thickness appear to be unstratified and are composed of olivine dolerites and microdolerites. In thicker bodies the stratification is much more pronounced and, in addition to olivine dolerites, they may contain more basic differentiates up to picrite gabbro-dolerites. However, the horizons usually are not well-sustained and the differentiates are found in the form of isolated spots.

An important structural characteristic of the flanges is the increased thickness of leucocratic rocks represented by gabbros and taxite gabbro-dolerites. The latter abound in inclusions of hornfels and metasomatically altered sedimentary rocks.

In some cases the differentiated massifs change in the flanges to elongated subhorizontal bodies composed of olivine gabbro-dolerites with loci of a leucocratic gabbro.

The breccioid rocks confined to the most intensively ramified zones of the intrusions are specific products of the flanges in the massifs. In the Western massif they form an almost continuous zone bounding the western and southwestern flanges of the intrusion [109]. The breccioid rocks are enclosed inbetween the numerous apophyses of the massif and abound in microdolerite bodies varying in shape and size. It is characteristic that regardless of the size of these bodies, they invariably exhibit a finely granular or vitreous chilled zone along the periphery. Fragments of contact metamorphic rocks also form part of the breccioid formations.

A brief description of metamorphic and metasomatic rocks

An extremely important characteristic of fully differentiated trap intrusions is the extensive development at their endo- and exocontacts of metamorphic and metasomatic rocks. These rocks form a large aureole around the intrusive bodies at both the upper and the lower exocontact of the intrusions. The greatest thicknesses of contact altered rocks are found, however, in the flanges of the massifs. Aureoles of altered rocks have been traced for up to 1.5-2km on the extension of magmatic bodies. The thickness of the altered rocks measures up to several hundreds metres, i.e. twice to four times the thickness of the flanges in the intrusion. Towards the intrusive body the aureoles taper down somewhat and farther down the dip of the massifs they have a relatively constant thickness. Isochemical products of the progressive stage of metamorphism, represented by hornfels and marbles [143], and rocks formed under regressive conditions [158 and 159] are extensively developed in the aureoles of altered rocks.

Products of the progressive stage, i.e. hornfels and marbles, sharply predominate in the lower contact of the intrusions. In the upper exocontact they are found in roughly equal proportions with products of the regressive stage. The main distinguishing characteristics of these rocks are first of all their being isochemical with the primary sediments; secondly, the polymineral composition of the rocks evolving from alumina-rich argillites, dolomites, dolomitic marls and anhydrites; and, thirdly, the intercalation of hornfels varying in composition on account of the chemical heterogeneity of the finely bedded sediments [143].

The highest-temperature hornfels formations found in the Talnakh ore field belong to the melilite-monticellite subfacies of the sanidine facies forming at temperatures of 900-1000°C [143]. p.45 Farther away from the contacts of the intrusion these hornfels become replaced by metamorphic products of the most wide-spread pyroxene facies (900-600°C), biotite-epidote-amphibole (600-700°C) and muscovite-chlorite (400-600°C) facies with their respective mineral associations (Table 8).

TABLE 8

Metamorphic rocks from the contact aureole of the Talnakh intrusion (after D.M. Turovtsev [143] and V.V. Yudina [158])

Metamorphic facies	The types of hornfels and the principal mineral associations			
	in silicon-rich terrigenous rocks	in dolomites, limestones, siliceous and argillaceous dolomites	in dolomite marls, anhydrites and dolomites	in calcareous and non-carbonate argillites
Sanidine facies (melilite-monticellite subfacies)	Quartz hornfels (Ml+Sil+Cord+Pl+ +Rt)	Periclase-forsterite-monticellite and monticellite-forsterite-spinel marbles (Mnt+Fo+Sp+Per+ Cal and Mnt+Fo+ Di+Sp+Cal+Ang)	Forsterite-monticellite-pyroxene hornfels (Fo+Mnt+Fas+Sp+ Cal+Ang)	-
Pyroxene	Pyroxene-plagioclase, quartz-feldspar and cordierite hornfels	Periclase-forsterite-spinel and diopside-forsterite-spinel marbles (Per+ +Fo+Sp+Cal and Di+Fo+Sp+ +Cal); diopside-phlogopite-forsterite marbles (Di+Fo+ Ph+Sp+Cal and Di+Fl+Gr+Cal+ Ang)	Plagioclase-olivine-diopside spinel-pyroxene and spinel-forsterite-pyroxene hornfels, anhydrite marbles with forsterite, spinel and periclase (Pl+Ol+ +Di+Bi+Mt+Cal and Di+Fo+Ph+Sp+Ang); pyroxene, garnet-pyroxene and phlogopite-diopside hornfels (Di+Fo+Fl+ Cal and Di+Fl+Gr+ +Cal+Ang)	Hypersthene-plagioclase-cordierite, plagioclase-quartz-cordierite and plagioclase-cordierite hornfels (Q+Ort+Pl+ +Hip+Bi+Mt and Ort+ +Pl+Cord+Mt); pyroxene-plagioclase and quartz-pyroxene-plagioclase hornfels (Q+ +Pl+Vol+Di and Q+Pl+ +Di+Mt);

(Table 8, continued)

Biotite-epidote-amphibole	Sandstones and siltstones, hornfels with garnet, actinolite, biotite, muscovite and chlorite	-	Phlogopite-tremolite hornfels and marbles (Ph+Trem+Ak++Mt+Cal+Ang)	Mica-chlorite schists with cordierite, quartz and albite (Bi+Mi+Cord+Pl++Q); actinolite-calcite-epidote and epidote-actinolite-albite hornfels, mica-chlorite schists with cordierite (Ak+Ep+Cal, Ak+Ep+Pl+Q+Mt and Bi+Ak+Pl+Q+Mt)
Muscovite-chlorite	Sandstones and siltstones with muscovite, hydromicas and calcite; spotted sericite-calcite schists	Marbles and serpentinites	-	Spotted sericite-chlorite schists with cordierite and calcite-chlorite hornfels

The metasomatic rocks associated with the Talnakh intrusion are localized within the contours of the metamorphic rocks and some of their types have been traced beyond the contours of hornfels. The main data on the metasomatites are presented in the works by V.V. Yudina [158 and 159], D.A. Dolin and B.N. Batuev [64], V.V. Zolotukhin, V.V. Ryabov et al. [75] dealing with the paragenetic and physico-chemical analyses of these rocks.

The metasomatites associated with trap intrusions have a number of important distinctive features: 1) Most of these rocks lack the typical metasomatic zoning and only some of them display microzoning around relatively thin veinlets; 2) The composition of the metasomatic rocks is controlled to a marked degree by the lithology of the wall rocks; 3) The development of identical mineral associations in intrusive, as well as in sedimentary-metamorphic rocks; and 4) Certain types of metasomatic rocks form telescoped deposits where different facies are not necessarily superimposed upon one another and the rocks appear to have evolved as a result of a continuous progressive process. These features account for the existence of a number of debatable assumptions in the works by the authors mentioned earlier. The general patterns of formation of the metasomatic rocks outlined in these works are, however, for the most part close. First of all it has been established that the types of the metasomatites evolved are strictly controlled by the lithological and chemical compositions of the exocontact rocks. Alkaline, feldspar and feldspar-quartz metasomatic rocks develop as a result of the replacement of sandstones, siltstones and argillites, as well as of extrusive rocks and olivine-free gabbro-dolerites. Magnesian and calcareous metasomatites replace dolomites, anhydrites, limestones, marls, microdolerites, dolerites, gabbros and gabbro-dolerites. Later low-temperature types of metasomatic rocks have been encountered amidst all the rock varieties listed above. The dependence of the type of the metasomatites on the composition of the primary rocks is most clearly pronounced in thin-bedded deposits.

The most debatable hypothesis concerns the development of magnesian metasomatic rocks. Different authors refer to these rocks forsterite, fassaite, varieties of spinel-fassaite with phlogopite, forsterite-spinel and forsterite-spinel-pyroxene rocks with anhydrite evolving from dolomites or dolomitic marls. It is very difficult to distinguish hornfels and metasomatites in these rocks. Furthermore, highly distinctive anhydrite-forsterite and forsterite-spinel veinlets cutting across gabbro-dolerites, occur in the intrusive rocks from the flanges of magmatic bodies. Identical relations have been observed for monticellite rocks. Monticellite calciphyres are extensively developed in the exocontact of the intrusions, but monticellite-spinel, monticellite-fassaite and sometimes even forsterite-monticellite veinlets intersect microdolerites and gabbro-dolerites. It is important to stress that these veinlets are associated with a magnesian-skarn microzoning [159]. A fassaite or fassaite-spinel zone forms in their exocontact and is succeeded by a forsterite or forsterite-spinel zone, whereas their central portion is composed of anhydrite or anhydrite and forsterite.

The forsterite +spinel association may, however, be also encountered in the form of fringes around xenoliths in gabbro-dolerites or as a relict association in taxitic gabbro-dolerites, but not be found in any of the other horizons of the intrusions. Rocks of this kind can probably be referred to magnesian skarns.

It may thus be seen that formation of magnesian metasomatites is a fairly complex process, and researchers have so far failed to obtain evidence on the basis of which the nature of these rocks can be interpreted with confidence. The only fact established beyond doubt is that at least a portion of these rocks formed during the postmagmatic stage. Magnesian metasomatites as a p.47 whole are among the earliest metasomatic rocks associated with differentiated traps.

Feldspathic rocks formed in alumosilicic sediments, some varieties of intrusive rocks and basalts, are another group of early metasomatic products. This group comprises albitites, quartz-albite and quartz-potash feldspar rocks that form veinlets or areal concentrations and replace the rocks listed above.

Calcareous metasomatites or skarnoids are the most extensively distributed varieties in the ore field. Similarly to the other types of metasomatic rocks, they are usually free of zoning. On the other hand the distribution of these rocks is distinctly telescoped relative to the magnesian metasomatites. For example, if the latter are localized in the zones adjoining the intrusion, then calcareous metasomatites form the outer part of the zone composed of altered rocks. The zoning of such locales thus generally corresponds to the zoning described by E.N. Gramenitskii [53] for magnesian-calcareous metasomatic rocks. It should be noted that calcareous metasomatites are much more widely distributed than the magnesian varieties, as a result of which there may often be encountered locales where magnesian metasomatic rocks are lacking. Among the skarnoids there have been distinguished a pyroxene-plagioclase, a garnet-pyroxene and a wollastonite- vesuvianite subfacies. The rocks of the pyroxene-plagioclase and garnet-pyroxene subfacies are distributed most extensively and develop in intrusive, as well as in sedimentary-metamorphic rocks. They compose massive zones with linear boundaries and form part of the breccioid rocks in the contact zone of the intrusion. Isolated veinlets display metasomatic zoning. The wollastonite-vesuvianite subfacies develops more locally and may be superposed on all the earlier metasomatic formations. Temperature analogues of these rocks are probably albite-prehnite metasomatites.

The latest hydrothermal metasomatic rocks are low-temperature formations developed in all the types of high-temperature metasomatites. In magnesian rocks they are represented by serpentine, serpentine-brucite and serpentine-brucite-valleriite veinlets, as well as by zones of areal replacement. Hydrogarnet-serpentine metasomatic rocks and a highly specific mineral association comprising hydrosilicates of calcium (xonotlite, pectolite), zeolites (gmelinite, analcite , natrolite and laumontite), as well as apophyllite and calcite, develop in calcareous rocks. Late formations/(products) are also represented by calcite veins that are extensively developed in the ore field.

In examining and describing the types of metamorphic and metasomatic formations found in the ore field, we attempted to show the general picture of the alterations that occur in the rocks around the intrusions hosting the copper-nickel ores localized in the exocontact of stratified intrusions. Some alterations of the rocks associated with formation of ores will be discussed farther on. It is only important to note that no specific type of alterations of sedimentary rocks has been established for sulphide ores. Copper-nickel mineralization may be superimposed on any type of hornfels or metasomatic rocks inducing recrystallization phenomena equally in both of them. We are therefore inclined to associate all the types of metamorphic and metasomatic rocks described above with the processes of formation of the intrusion and to regard them as its contact aureole, on which the ore mineralization with its own alteration aureole have been superposed. The low-temperature hydrothermal phenomena with which the processes of ore metamorphism and redeposition of mineral components are associated, are the only exception.

Copper-nickel sulphide ores p.48

The deposits of the Talnakh ore field are the most striking example of the multiplicity of forms in which sulphide ores occur in stratified intrusions. The discovery and subsequent studies of these deposits yielded qualitatively new evidence for research on the processes of ore formation associated with trap magmatism. One of the main hypotheses pertaining to geology of the Noril'sk deposits has been developed further: it postulates the unity of the structural geological factors controlling the localization of magmatic massifs and sulphide ores.

In addition to that the notion that mineralization occurs in stages and the idea that within the deposits there form ore zones differing in the type of their constituent copper-nickel ores and in their position relative to the stratigraphic intrusion, have been formulated for the first time.

The ore zone of the deposits from the Talnakh ore field comprises the following types of ores: impregnated ores in the horizons of the Talnakh intrusion, massive ores concentrating mainly in the lower exocontact of the intrusion and, less often, in its endocontact; veinlet-impregnated ores in the exocontact of massive sulphide ore deposits; veinlet-impregnated ores in the upper exocontact of the intrusion; and breccioid or, less often, veinlet-impregnated ores in the pinch-out zones of the intrusive massifs.

Impregnated ores in intrusive rocks. Impregnated ores are confined mainly to two horizons of stratified intrusions, i.e. to the horizons of picrite and taxite gabbro-diorites (fig. 9). From the viewpoint of morphology this is the simplest type of mineral concentrations in the major part of the massif, since it is found virtually everywhere due to the well-sustained character of the two horizons. The distribution of sulphides within these horizons is also relatively constant.

The upper part of the picrite gabbro-dolerites and, considerably less often, the olivine-biotite gabbro-dolerites adjacent to them, contain fairly low concentrations of impregnated sulphides, which gradually increase in quantity downwards in the section of the picrite horizon. The maximum concentration of impregnated sulphide ores has been recorded in the middle and lower parts of the picrite gabbro-dolerites and in the upper and middle portions of the taxite gabbro-dolerite horizon. The concentration of sulphides gradually decreases towards the lower contact of the intrusion. Against the backdrop of the relatively smooth variations in the content of sulphides, there may be noticed a certain lack of uniformity in the distribution of ores at isolated loci. Strata up to 70cm in thickness with increased or below-average contents of sulphides may be observed in isolated vertical intersections of the horizon of picrite gabbro-dolerites.

. The lack of uniformity in the distribution of sulphides in taxite gabbro-dolerites is evident from the presence in that horizon of relatively large schlieren of massive sulphides.

The horizons containing impregnated ores exhibit the most complex structure in the flanges of the intrusive massifs. As a result of the separation of the intrusion into a series of apophyses, the integral ore-bearing horizon divides into several discrete sulphide-rich zones alternating with zones containing little or no sulphides. In the picrite gabbro-dolerites the zones devoid of ore progressively increase in number towards the pinch-out regions of the massif. Picrite gabbro-dolerites completely barren of mineral concentrations, are highly characteristic formations in the flanges of the intrusion. The taxite gabbro-dolerites invariably contain impregnated ores, even when their individual apophyses are only a few centimetres in thickness. It should be stressed that this type of structural complexity of the horizon with impregnated ores is more characteristic of the parts of the intrusions localized in sulphate-carbonate beds. In terrigenous rocks, where the flanges have a simpler structure, the ores may persist to the point where the intrusion pinches out.

Massive ores. In the Talnakh ore field massive sulphide ores are localized in the rocks underlying the stratified intrusion and, partly, in its lower endocontact zone [140]. Massive ores occur virtually throughout the ore horizon, but in some parts of the horizon they merely form thin veinlets or veinlet-impregnated concentrations, while in others they occur in the form of large bodies or massive deposits. The alternation of the locales varying in the degree of concentration of sulphide materials affects the structure of the horizon as a whole. The distribution of large concentrations of massive sulphide ores and veinlets displays a number of distinctive features. The largest deposits are localized along the axial zones of the intrusive bodies and stretch down the dip of the massifs. Furthermore, p.49

it has been established that low-angle folded structures in the lower exocontact of the massifs also play a certain role in the distribution of sulphide deposits. Large concentrations of massive sulphide ores are often confined to dome-like elevations of sedimentary-metamorphic rocks, but the succeeding downwarped locales contain small quantities of ores. At the points of transition from elevated to downwarped locales the ore bodies either markedly decrease in thickness, or divide into a series of thin stringers and eventually pinch out. Wherever the base of the intrusive massif bends sharply, the ore body may pass from sedimentary-metamorphic rocks into the endocontact zone of the intrusion that is located at the same hypsometric level (fig. 10). This produces substantial changes in the morphology of the ore bodies.

In sedimentary-metamorphic rocks large ore bodies are in the form of sheets or monolithic lenticular deposits stretched in the direction of the dip of the intrusive massifs, or, less often, are isometric in shape. It is highly characteristic that these deposits have commonly no direct contact with the stratified intrusion, since magmatic rocks are separated from the ores by interlayers of sedimentary-metamorphic rocks that may be devoid of sulphide minerals.

The greatest thickness of the bodies is in their axial part. Towards the flanges the inclusions and interlayers of sedimentary-metamorphic rocks increase in number and the monolithic bodies divide into a series of thinner parallel veins.

The ore bodies localized in intrusive rocks may be differentiated into two types. One of them is represented by large deposits of a great length that are close in morphology to the ore bodies occurring in sedimentary-metamorphic rocks. Given this type of bodies, e.g. the bodies associated with the branches of the intrusion in the eastern part of the ore field and its western part (i.e. the Kharaelakhskii branch), the transition of the ore deposit from sedimentary-metamorphic into magmatic rocks is not accompanied by any significant changes in their morphology or thickness.

On the other hand there have been observed locales in the ore field, where the transition of massive ores from sedimentary-metamorphic into magmatic rocks results in significant complications in the morphology of the ore bodies. In place of one single large deposit there arises a system of variously oriented veins and veinlets. We refer such bodies to the second type. They are tabular in shape with parallel contacts and a vein zone resembling a stockwork, in the endocontact of the intrusion. At the points of intersection of the veins there may form large blocks of massive sulphides or ore pillars with rectilinear boundaries. The largest bodies commonly pinch out at obtuse angles or separate into several thinner veins. Another feature characteristic of these bodies is that they may form steep bends and, in doing so, change from one hypsometric level to another with amplitudes of several metres. The olivine gabbro-dolerites occurring inbetween the veins are commonly devoid of impregnated sulphides and may only sporadically contain fairly high concentrations of impregnated sideronite.

In the locales examined the ore veins are confined to three systems of zones: subhorizontal or low-angle zones parallel p.51 to the contacts of the intrusion; zones at angles of 35-50°; and high-angle or vertical zones with angles of 70-90°. Most of the veins are subhorizontal; those occurring at an angle or having a subvertical orientation are fewer.

These aspects of morphology of massive sulphide ore bodies in intrusive rocks can probably be explained by the distinctive premineral tectonics of the area. The systems of variously oriented veins and veinlets may be associated with large bodies of the first type. At a number of loci in the ore field there have been detected subvertical or inclined apophyses of the main ore body, but their total number is usually small.

Fig.9

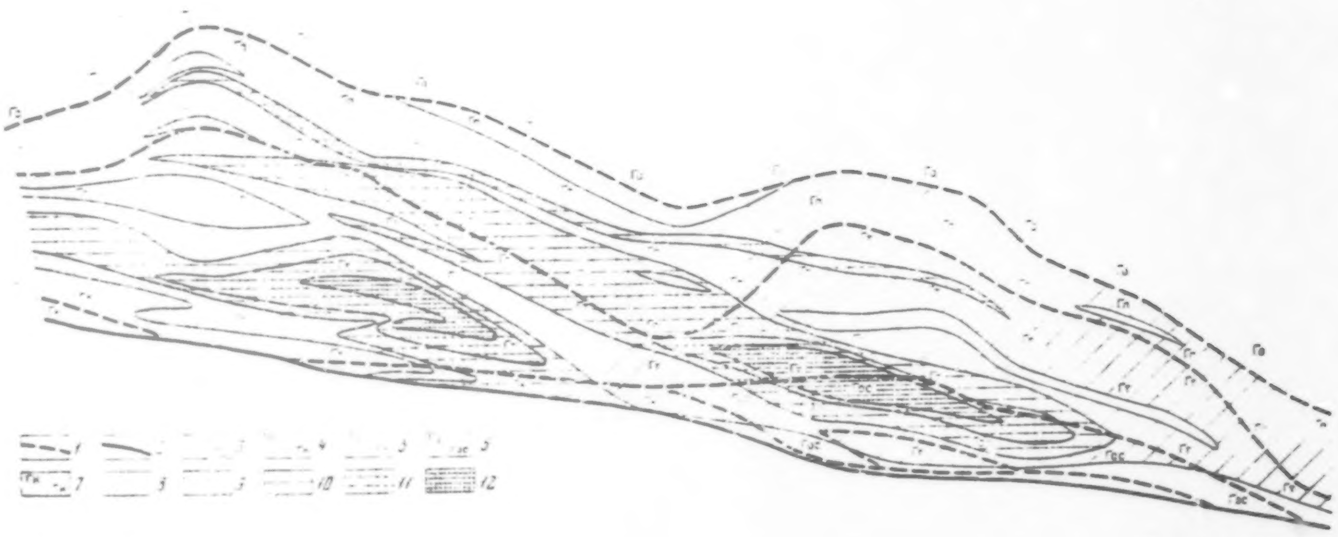
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Fig.10

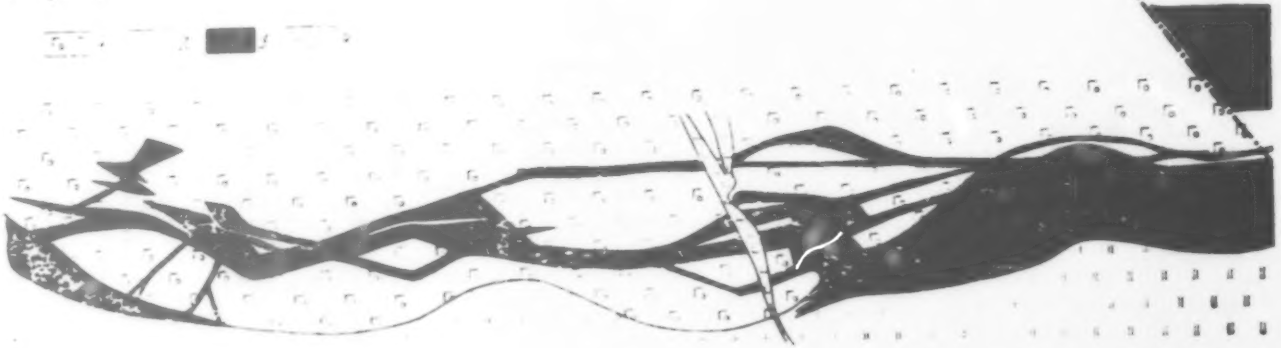

Fig. 9

Distribution of impregnated sulphide ores in the section of the Talnakh intrusion.

1-The contour of differentiates in the intrusion; 2-Isolines of the contents of sulphides; 3-Olivine-containing and olivine gabbro-dolerites; 4-Picrite gabbro-dolerites; 5-Taxite gabbro-dolerites; 6-Equigranular olivine-containing gabbro-dolerites; 7-Contact gabbro-dolerites; 8-12---Weighted mean content of sulphides: increase in the density of hatching corresponds to the rise of the relative concentration of sulphides in the different horizons of the intrusion.

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Fig. 10

Changes occurring in morphology of massive sulphide ore bodies with transition of these deposits from sedimentary-metamorphic into intrusive rocks

1-Olivinic gabbro-dolerites; 2-Contact-metamorphic rocks; 3-Massive ores; 4-Postmineral dikes of diabases.

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Some of the lodes examined are localized in prototectonic fissures, but most of them fill the cavities of tectonic fissures, including those resulting from relatively large-scale block displacements. In order to find a plausible explanation for this phenomenon we should examine some of the characteristic aspects of the attitude of these locales in the framework of the ore field. The parts of the intrusions enclosing large ore bodies are localized relatively far from the Noril'sk-Kharaelakhskii fault, the main structure of the ore field. The intrusive body located east of the fault is confined, for example, to the part of the ore field with relatively weak disjunctive tectonics. The intrusive body in its western part (the Kharaelakhskii branch) is located at a considerable distance from the fault zone, even though the scale of tectonic disturbances in the western part of the field is significantly greater than in its eastern part. The intrusive massif, in which sulphide veins form a stockwork-like zone, is situated directly in the fault belt forming the so-called central graben. As a result of special structural studies by V.F. Kravtsov, Yu.N. Sedykh [101 and 102] and other researchers it has been demonstrated that tectonic activities continued for a long time in the Noril'sk-Kharaelakhskii fault during the pre-intrusive and postmineral periods. The intensive block faulting and formation of cavities in the locale discussed appear to be related to the fragmentation of the intrusive massif which preceded the injection of sulphide material. In our opinion this conclusion is of great importance for studies of the conditions under which massive ores formed.

The numerous submeridional fissures along which isolated parts of the deposits, localized in sedimentary-metamorphic or intrusive rocks, become displaced, are associated with postmineral tectonic movements. Structures of this kind are found everywhere, and in the locales where they are developed most intensively, the horizon of massive ores has a step-block structure.

These are the main features of structure of the massive ore horizon and the main morphological characteristics of the ore bodies composing that horizon. We should, however, also examine some of the patterns of alteration of the mineral composition of the ores in conjunction with the distinctive morphology and attitudes of the massive sulphide bodies. In this plan one of the most interesting characteristics of massive ores is that transition of the ore bodies from sedimentary-metamorphic into intrusive rocks is accompanied not only by morphological changes, but also by significant alterations of their mineral composition. The ore bodies found in the exocontacts of the intrusions are composed mainly of the so-called "pyrrhotite" ores. Their p.52
essential constituent minerals are pyrrhotite and, to a lesser degree, pentlandite and chalcopyrite. Talnakhite (talnachite), mooihoekite (mooihoeckite) and cubanite ores bearing the names of their essential sulphide components, predominate in intrusive

rocks. These ores contain no minor quantities of pyrrhotite. As a result of alterations in the composition of the ores there arise bodies with a complex mineral zoning. All the mineral varieties of massive ores and their zoning patterns are described in detail in the appropriate chapters farther on. We shall merely note here that with regard to the mineral diversity of its ores, the Talnakh ore field is a unique geological formation having no equals among the deposits of the world's copper-nickel provinces.

Veinlet-impregnated and breccioid ores. Veinlet-impregnated ores are found in the roof, as well as at the base of the intrusive massifs. At the base of the massifs they occur in the exocontact of massive sulphide ore bodies. It has been observed that ore concentrations of this type are associated with the deposits confined to the flanges of the intrusive massifs.

The ores concentrate for the most part in sedimentary-metamorphic rocks at the base of the deposits and, to a lesser degree, in the overlying sediments. When bodies of massive sulphides occur in intrusive rocks, the latter may also contain highly specific impregnated ores.

Impregnated and veinlet-impregnated ores occur in sedimentary-metamorphic rocks, in the pinch-out zones of massive sulphide deposits or develop around these deposits in the form of a continuous aureole recapitulating the outlines of the deposit. The ore bodies commonly have no clearly defined natural boundaries, but gradually go over into the gangue. These ore bodies are irregularly shaped with swells or loci varying in thickness. They may be tabular in shape and stretch in the form of relatively narrow belts along the strike of several massive sulphide deposits.

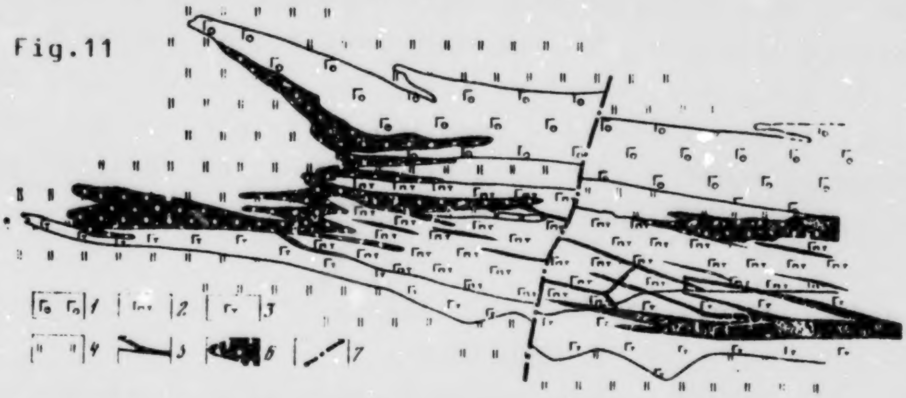
The ores found in the roof of the intrusive massifs are very similar to those localized in the exocontacts of the massive sulphide bodies. They resemble the latter in composition, form of sulphide concentrations, and in the ratios of sulphides and silicates, but have a relatively limited extent. The most characteristic feature of their localization is the direct association of this type of ores with the zone of fissures of the Noril'sk-Kharaelakhskii fault, particularly with the system of tectonic disturbances of the central graben and so-called western faults. This type of mineral concentrations is practically unknown east or west of that tectonic system, outside its boundaries. The results of observations available at present are insufficient for determining the forms of the relationship between the tectonic dislocations and mineral concentrations, but the existence of such a relationship is beyond doubt. First of all the ore zone as a whole stretches only along these tectonic structures. Secondly, the maximum thicknesses are confined to the parts of the zone directly adjacent to the fault-like flexure-like structures and to the tectonic disturbances proper. The ore body pinches out fairly rapidly in the locales adjoining the faults, and west of these locales the intensity of mineralization decreases gradually, the initially integral body of impregnated ores decreases in thickness and breaks up into relatively thin tabular bodies containing mineral concentrations of the same type.

The ore zone examined gradually plunges north and may eventually become conjugated in that direction with the mineral locales from the lower exocontact of the intrusive body and with the massive and veinlet-impregnated ores localized in them. One of the arguments in support of this viewpoint is the presence of relatively small sulphide ore veins in the mineralized zone from the upper exocontact of the intrusion. These ores are identical in their texture and composition to the massive ores from the lower exocontact. Furthermore, these two types of ore concentrations exhibit similar patterns of alteration of their mineral composition and identical patterns of zoning in the distribution of the mineral assemblages of sulphides. p.53

The veinlet-impregnated ores from the upper and lower contacts of the intrusive massifs are thus the same type of mineral concentrations, and the unusual localization of the ores in the superintrusive zone is due to the specific tectonic conditions in the locales adjoining the regional disjunctive structure.

Sulphide ores differing markedly in structural characteristics from the veinlet-impregnated ores discussed above, develop in the western part of the ore field, in the metamorphic and metasomatic exocontact rocks from the flange zone of the intrusive massif. In their bulk these ores are breccioid in appearance with sulphides acting as cement and filling the interspaces between the fragments of metamorphosed or metasomatically altered sedimentary rocks. The ores have inherited their structure from the rocks in which they are emplaced. As was shown earlier, breccioid rocks are the most widely distributed type of exocontact formations in the western part of the ore field. They are localized inbetween the apophyses of the intrusive body and stretch for considerable distances from the flange zone of the intrusion. Sulphide ores concentrate mainly in the part of the field composed of breccioid rocks, which directly adjoins the flanges of the intrusion, even though the breccioid rocks themselves are much more extensively distributed. This determines the main morphological characteristics of the zone with breccioid ores (fig. 11). This zone has a highly intricate structure, since the ores occur inbetween the apophyses of the intrusion and around their flanges bounding them in the form of a fringe. The ores thus form an almost continuous ore mantle in front of the intrusive body recapitulating the outer contours of that body. We should also emphasize certain other characteristics of this type of mineral concentrations. First of all the mineral material becomes deposited almost exclusively in the sedimentary-metamorphic country rock; the blocks of magmatic rocks are almost always devoid of ores. The only minerals established in gabbro-dolerites ar[illegible] small-scale concentrations of sideronitic impregnated sulphides [illegible] the selvages of the bodies composed of breccioid ores. Seco[illegible]ince isolated locales of the breccioid rocks represent undist[illegible]ed blocks of primarily schistose metamorphosed rocks, superimposition of ores on such locales leads to the appearance among the breccioid ores of impregnated or veinlet-impregnated structural types of mineral concentrations with inherited primary types of structure. p.54

Fig. 11



Distribution and relationship of massive and breccioid ores in the flanges of the Talnakh intrusion. Diagrammatic representation of the section from the northwestern part of the Talnakh ore field. Different vertical and horizontal scales.
1-Olivine gabbro-dolerites; 2-The horizons of displaced picrite and taxite gabbro-dolerites; 3-Taxite gabbro-dolerites; 4-Contact-metamorphic and metasomatic rocks; 5-Bodies of massive sulphide ores; 6-Bodies of breccioid ores; 7-Tectonic disturbances.

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Thirdly, the most important characteristic of the mineral concentrations found in the zone examined is the fairly frequent presence of loci composed of massive sulphide ores amidst the breccioid and veinlet-impregnated ores. In the presence of mineral zoning in the ore body, massive ores may constitute the axial zone in which the succession of mineral associations begins.

It is highly important to examine the relationship of this type of mineral concentrations with the massive ores that are localized either below the breccioid ores or, partly, at a hypsometric level close to that of the breccioid ores.

The western part of the ore field is one of the locales, where bodies of massive sulphides invade intrusive rocks. As a result of that, in addition to a large massive ore body, there arise in gabbro-dolerites variously oriented veinlets and veins intersecting the intrusion and forming the zone of break-up or separation of the main deposit. This zone has been traced for a considerable distance from the main deposit, as far as the locales with breccioid ores (see fig. 11). This evidences that massive and breccioid ores are genetically related formations and that their structural differences are a result of specific structural-tectonic conditions in the zones of ore deposition.

Some data on the relationship of massive, veinlet-impregnated and breccioid ores with the country rock

At the contacts with different types of ores the country rock is altered in a variety of ways. At the contacts of massive ores with intrusive rocks these alterations are commonly minor. At the contacts with sedimentary-metamorphic rocks they are more substantial and are controlled by the lithology of the rocks.

As was mentioned earlier, massive ores form sharp contacts with gabbro-dolerites (Table I,a and b). The inclusions of magmatic rocks encountered occasionally in sulphide veins, are of the nature of xenoliths that are virtually unaffected by the nearby presence of ores. In the contact-line parts of the veins magnetite increases in content and forms a thin fringe in the endo-contact of the bodies or a narrow (1-3mm) zone in their exocontact.

In the exocontact of intrusions massive ores are localized in the rocks altered as a result of the contact metamorphism related to the injection of the intrusive massifs. The rocks are represented by compositionally diverse hornfels, skarnoids, marbles and metamorphosed terrigenous-carbonaceous sediments. In addition to that, at the contacts of massive ores there have been recorded specific alterations of the rocks metamorphosed earlier, as a result of which the aureole of sulphide metamorphism is superposed on the aureole of metamorphic alterations surrounding the intrusion.

Prior to examining the alterations of the country rock, we wish to note some distinctive aspects of the alterations observed at the endocontacts of the ore bodies.

As was mentioned earlier, the bodies of massive sulphide ores form fairly gradual contacts with the country rock on account of the presence of a transitional zone with impregnated ores, where sulphides contain large quantities of non-metallic mineral relicts. These zones are commonly enriched in magnetite to a marked degree. At the contacts with compact fine-grained pyroxene hornfels the transitional zone is partly composed of recrystallized larger-grained rocks with drop-like isometric grains of sulphides (Table II,a). The phenomena associated with the replacement of the country rock by sulphides are clearly observable in the chlorite-albite and chlorite-feldspar rocks with characteristic spherical grains of minerals. Impregnated ores with sphaerolitic sulphide-silicate aggregates recapitulating the texture of the sedimentary-metamorphic rocks (Table II,b), form in the transitional zone as a result of these phenomena. p.55

Rather distinctive phenomena have been observed at the contacts of massive ores with feldspathic rocks. Very unusual rocks composed of pegmatoid quartz-potash feldspar aggregates (Table II, c) form in these locales. Inclusions of these rocks are fairly widely distributed within the ore bodies around the xenoliths of a corresponding composition. In the parts of the ore bodies adjoining the contacts they may also form a border around the sulphide deposit or form part of the transitional zone, in which these rocks are heavily impregnated with sulphides.

In some cases there have been observed quartz-feldspar veinlets cutting across the hornfels in which the sulphide vein is localized. It is important to note that these formations are not zoned as a rule and correspond in composition to the most readily fusible fraction of terrigenous rocks. The thicknesses of the country rock do not depend on the thickness of the ore bodies.

All these characteristics, particularly the association of the wallrock formations with definite lithological types of contact hornfels, evidence that the quartz-feldspar rocks formed in the process of partial fusion of the country rock.

Large-grained biotite-potash feldspar rocks and potash-feldspar-pyroxene rocks are among the wall rocks evolving as a result of the partial fusion of quartz-free pyroxene-feldspar hornfels. In the event of their occurring in remote locales away from the contact with sulphide deposits, there form isolated spots of larger-grained recrystallized rocks with idiomorphic crystals of potash feldspar and pyroxene. In the locales that are close to the contacts of ore deposits, the rocks become even larger-grained and, in addition to pyroxene, there appears biotite. Large grains of pyroxene penetrating from the contact rocks into the sulphide vein in the form of idiomorphic crystals, form at the contacts of the vein. Inclusions of sheath-like* idiomorphic clinopyroxene crystals (Table III,a) completely surrounded by sulphides are extremely wide-spread in the same locales of the veins. Highly interesting alterations have been observed in such instances in the composition of the pyroxenes (Table 9).

Clinopyroxene is represented in the hornfels (Table 9, sample 9400-8) by a calcium-rich aluminous optically anomalous variety of the type of fassaite with the content of iron $f_{at}=0.14-0.22$. In the zones of initial recrystallization there arises in the hornfels an alumina-poor clinopyroxene with a lower concentration of calcium and a higher (up to $f_{at}=0.20-0.28$) content of iron (Table 9, sample 9400-6). All the subsequent alterations proceed along the lines of the concentration of iron increasing further to $f_{at}=0.30-0.33$, while the contents of the other essential components remain relatively constant. A characteristic phenomenon is the appearance of chromium in the euhedral clinopyroxene crystals from the inner part of the sulphide vein (Table 9, samples 9400-2 and 9400-1). It is also important to note that these clinopyroxenes, found at equilibrium with sulphides, are very close in composition to the clinopyroxene from olivine-containing and olivine gabbro-dolerites.

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* euhedral? Translator.

In the process of remelting the chemical composition of the rocks (Table 10, samples 9420 and 9421) surrounding the sulphide veins alters as follows: the content of the silica-alumina-potassium component increases, that of the magnesian-calcareous constituent decreases, and the concentrations of sodium, water and sulphur sulphate remain practically unchanged. The behaviour of iron varies depending on the concentration of metallic components in the rocks. Another interesting factor is the composition of the melted out rocks (Table 10, sample 4922-3) cutting across the alkali-free pyroxene hornfels (sample 9422-1 and 2).

The other noteworthy contact alterations associated with massive ores are the wide-spread recrystallization phenomena in pyroxene-garnet skarnoids, forsterite, fassaite and monticellite hornfels and metasomatic rocks, and marmorization in sulphate-carbonate beds. The latter undergo no other types of contact alterations.

It may thus be seen that alterations of the wall rock at the contacts with massive sulphide ores are essentially of two types, depending on the composition of the country rock. p.56 The most wide-spread phenomena are recrystallization and increase in the size of grains conjugated with compositional changes of some of the minerals and with formation of silicate phases that may be at equilibrium with sulphides. Remelting of the rocks with formation of feldspathic or quartz-feldspathic products, which may migrate together with sulphides for relatively small distances from the site of fusion, is a less wide-spread phenomena. Quartz-feldspar rocks form in sedimentary beds containing relatively readily fusible components.

Mineral concentrations of other morphological types (veinlet-impregnated or breccioid) may be localized in virtually any of the rocks from the exocontact aureole of the stratified intrusion.

TABLE 9

Composition of clinopyroxenes from the contact zone of massive ores (weight %, X-ray microanalysis)

Sample numbers	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Cr_2O_3	Total	f_{at}	Ca_{at}	Observations
9400-1	51.5	0.66	2.1	9.8	0.17	12.3	22.5	0.25	0.22	99.50	0.309	0.476	Idiomorphic euhedral crystals in the central part of the ore body
	52.0	0.58	1.8	9.5	0.17	13.3	21.3	0.13	0.10	98.88	0.286	0.451	
9400-2	52.5	0.63	2.3	9.6	0.17	12.5	22.8	0.23	0.36	101.09	0.301	0.478	An euhedral crystal at the contact of the ore body with the wall rock
	53.0	0.59	1.9	10.2	0.20	11.4	23.1	0.22	0.28	100.89	0.334	0.492	
	51.8	0.48	1.8	9.6	0.20	12.3	22.8	0.29	0.33	99.60	0.305	0.481	
	51.5	0.82	2.3	9.5	0.19	12.4	22.8	0.31	0.40	100.22	0.301	0.480	
9400-6	54.0	0.46	1.0	6.8	0.16	14.7	22.2	0.27	-	99.59	0.206	0.463	Recrystallized grains of pyroxene intergrown with potash feldspar in sedimentary-metamorphic rocks
	53.7	0.22	1.2	8.8	0.10	12.8	23.1	0.29	-	100.21	0.278	0.484	
	52.8	0.42	1.4	7.9	0.18	14.8	21.4	0.31	-	99.21	0.231	0.445	
	52.6	0.39	1.0	7.6	0.15	14.4	22.2	0.24	-	98.58	0.229	0.461	
9400-8	55.5	0.28	1.0	4.6	-	14.1	25.4	0.28	-	101.06	0.155	0.523	Pyroxenes from pyroxene-feldspar hornfels
	55.1	0.38	1.1	4.2	-	14.6	25.3	0.30	-	100.98	0.141	0.517	
	50.1	0.87	4.3	6.3	-	12.2	25.1	0.32	-	99.19	0.225	0.534	
	50.8	1.4	3.5	5.2	-	13.2	25.3	0.26	-	99.66	0.181	0.530	

Crystallochemical formulas:

1. $(Na_{0.018}Ca_{0.911})_{0.929}(Mg_{0.692}Fe_{0.310}Mn_{0.005}Al_{0.039}Ti_{0.019}Cr_{0.007})_{1.072}(Si_{1.945}Al_{0.055})_2O_6$
2. $(Na_{0.01}Ca_{0.864})_{0.874}(Mg_{0.751}Fe_{0.301}Mn_{0.005}Al_{0.049}Ti_{0.017}Cr_{0.003})_{1.126}(Si_{1.969}Al_{0.031})_2O_6$
3. $(Na_{0.017}Ca_{0.908})_{0.925}(Mg_{0.692}Fe_{0.298}Mn_{0.005}Al_{0.052}Ti_{0.018}Cr_{0.01})_{1.075}(Si_{1.951}Al_{0.049})_2O_6$
4. $(Na_{0.016}Ca_{0.927})_{0.943}(Mg_{0.636}Fe_{0.32}Mn_{0.006}Al_{0.07}Ti_{0.017}Cr_{0.008})_{1.057}(Si_{1.086}Al_{0.014})_2O_6$
5. $(Na_{0.021}Ca_{0.921})_{0.942}(Mg_{0.691}Fe_{0.303}Mn_{0.006}Al_{0.033}Ti_{0.014}Cr_{0.01})_{1.057}(Si_{1.953}Al_{0.047})_2O_6$
6. $(Na_{0.023}Ca_{0.915})_{0.938}(Mg_{0.692}Fe_{0.30}Mn_{0.006}Al_{0.044}Ti_{0.023}Cr_{0.012})_{1.077}(Si_{1.942}Al_{0.058})_2O_6$
7. $(Na_{0.019}Ca_{0.884})_{0.903}(Mg_{0.815}Fe_{0.211}Mn_{0.005}Al_{0.044}Ti_{0.013})_{1.088}Si_{2.008}O_6$

Crystallochemical formulas (continued):

8. $(Na_{0.021}Ca_{0.924})_{0.945}(Mg_{0.713}Fe_{0.275}Mn_{0.003}Al_{0.053}Ti_{0.006})_{1.05}Si_{2.006}O_6$

9. $(Na_{0.022}Ca_{0.857})_{0.879}(Mg_{0.824}Fe_{0.247}Mn_{0.006}Al_{0.034}Ti_{0.012})_{1.123}(Si_{1.972}Al_{0.028})_2O_6$

10. $(Na_{0.017}Ca_{0.895})_{0.912}(Mg_{0.808}Fe_{0.239}Mn_{0.005}Al_{0.024}Ti_{0.011})_{1.087}(Si_{1.98}Al_{0.02})_2O_6$

11. $(Na_{0.02}Ca_{0.994})_{1.014}(Mg_{0.768}Fe_{0.14}Al_{0.043}Ti_{0.008})_{0.959}Si_{2.027}O_6$

12. $(Na_{0.021}Ca_{0.989})_{1.01}(Mg_{0.794}Fe_{0.128}Al_{0.047}Ti_{0.011})_{0.98}Si_{2.009}O_6$

13. $(Na_{0.023}Ca_{1.007})_{1.03}(Mg_{0.681}Fe_{0.197}Al_{0.066}Ti_{0.025})_{0.969}(Si_{1.876}Al_{0.124})_2O_6$

14. $(Na_{0.019}Ca_{1.008})_{1.027}(Mg_{0.731}Fe_{0.162}Al_{0.041}Ti_{0.039})_{0.973}(Si_{1.888}Al_{0.112})_2O_6$

TABLE 10

Chemical composition of remelted rocks around the bodies of massive sulphide ores

Sample Numbers	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O
9420-1	43.88	0.91	10.55	0.68	4.77	0.11	16.21	15.11	0.28
9420-2	46.00	0.50	12.21	1.33	4.87	0.22	8.44	20.19	0.18
9420-3	49.52	1.91	14.06	2.56	8.33	0.60	10.70	0.13	0.35
9421-1	48.36	0.52	16.02	1.46	9.17	0.53	4.17	3.09	0.35
9421-2	50.84	0.67	13.53	1.71	8.94	0.06	3.91	3.99	0.38
9421-3	51.40	1.22	17.00	1.76	4.28	1.11	9.03	0.13	0.18
9422-1	41.64	0.58	10.70	1.33	5.36	0.17	12.75	23.53	0.05
9422-2	41.44	0.71	10.57	0.80	5.71	0.15	13.53	22.67	0.08
9422-3	47.74	1.80	12.56	2.77	7.63	0.17	4.77	12.77	0.22

TABLE 10, continued

Sample numbers	K_2O	H_2O+	H_2O-	P_2O_5	S-sulphide	SO_3	CuO	NiO	Total
9420-1	3.38	1.22	0.12	0.72	0.82	0.13	0.85	0.08	99.65
9420-2	2.05	1.19	0.10	0.52	0.39	0.35	0.69	0.04	99.18
9420-3	8.0	1.93	0.38	0.40	0.34	0.17	0.27	0.14	99.79
9421-1	11.7	1.44	0.12	0.03	3.22	0.19	1.10	0.32	101.79
9421-2	11.59	0.81	0.23	0.63	3.29	0.25	0.78	0.15	101.76
9421-3	10.3	1.55	0.16	0.80	0.81	0.10	0.97	0.24	101.04
9422-1	0.10	0.86	0.03	0.96	1.79	0.23	0.66	0.78	101.52
9422-2	0.48	1.18	0.14	0.88	1.69	0.27	0.72	0.34	101.36
9422-3	5.65	1.56	0.27	0.46	1.40	0.18	0.64	0.58	101.17

FOOTNOTE. The numbers of the samples indicate different locales of sedimentary-metamorphic rocks surrounding the deposits of massive ores. 1-The most remote locales; 2-Intermediate; and 3-Contact rocks.

Mineral concentrations have been found in all the types of hornfels. Ores are particularly widely distributed in rocks of the pyroxene facies of metamorphism, in magnesian and magnesian-calcareous hornfels, in calcareous and dolomite marbles, in compositionally diverse calciphyres, feldspar or feldspar-quartz rocks. Sulphides have been encountered in association with forsterite, spinel, monticellite, fassaite, garnet and diopside that compose the systems of veinlets cutting across the intrusive rocks. Ores are very extensively developed in skarnoids.

The main types of country rocks, the characteristic aspects of their relationship with sulphide ores and the principal silicate associations found in intergrowths with sulphides, are presented in Table 11.

A noteworthy fact is the constant nature of the relationship between the sulphides and nonmetallic minerals in the above rocks. Sulphides partly replace these minerals, but for the most part they form xenomorphic aggregates localized in the interstices of idiomorphic crystals in nonmetallic minerals. p.58 These crystals are commonly large relative to the crystals of the same minerals in the primary rocks. Different types of the country rock may contain intergrowths of sulphides with unaltered grains of forsterite, monticellite, fassaite, phlogopite, diopside, garnet, potash feldspar, quartz, crystals of anhydrite or calcite. This type of associations evidently developed mainly as a result of recrystallization phenomena during the superposition of sulphide mineralization on these rocks (Table IVa and b).

Somewhat different relationships are characteristic of the intergrowths of sulphides and silicates arising as a result of the superimposition of sulphide mineralization on gabbro-dolerites. In these cases the sulphides become localized in the interstices of the rock-forming minerals, as a result of which the rocks may acquire a sideronitic texture. The sulphides commonly assume the textural position of the pyroxene grains, but the plagioclases retain their idiomorphic aspect. One of the distinctive features of these rocks is the appearance therein of quartz that is not characteristic of the other gabbro-dolerite varieties from the bottom part of the intrusions. Its formation may probably be regarded as a consequence of the sulphide-silicate reactions occurring during the mineralization of magmatic rocks. It is equally possible that in the course of these processes the rocks also undergo recrystallization.

It may thus be seen that all the types of copper-nickel ores exhibit distinctive features of relationship with the sedimentary-metamorphic and magmatic rocks enclosing these ores. Recrystallization of the rocks and replacement of silicates by sulphides are the most wide-spread phenomena. Other characteristic phenomena are remelting of different varieties of sedimentary-metamorphic rocks on the one hand, and certain reactions resulting in formation of magnetite and, possibly, quartz. p.58

As is evident from our analysis of the relationship between the ores and the country rock, the emplacement of ore is preceded by an intensive metamorphic and metasomatic reworking of sedimentary beds that is related to the injection of sulphide-bearing intrusions and occurs within the temperature interval of 1000° - 400°C. Deposition of ores is associated with a new high-temperature stage of alterations of the already metamorphosed rocks. The temperature range of these alterations is roughly 1100° to 700°C. These data and the structural relationships of the ores and intrusive rocks that have been discussed above, evidence that the sulphide material envades the zone of ore deposition with a certain time lag relative to the injection of the intrusions, and represents a later magmatic subphase.

Subsequent to the deposition of sulphide ores there occur only relatively small-scale low-temperature alterations affecting the ores themselves as well as their wall rock. The alterations are largely restricted to the ore bodies and do not spread farther than 1-3m outside their boundaries. The alterations of the country rock consist of the replacement of earlier minerals by serpentine, brucite, chlorite, epidote, vesuvianite and hydrogarnet. The concomitant alterations of the ores are in the form of the replacement of primary sulphides by pyrite, magnetite, valleriite, tochilinite, polydymite, arsenides and sulpho-arsenides of nickel, iron and cobalt.

TABLE 11

Types of country rock and relationship of sulphide ores with metamorphic and metasomatic rocks

Stages	Metamorphic and metasomatic rocks		Types of copper-nickel ores	Relationship of ores with metamorphic and metasomatic rocks	
	rocks	major mineral facies		Major alterations	Minerals at equilibrium with sulphides
Progressive	Magnesian skarns (?)	Fo+Ph+Sp	Massive, veinlet-impregnated or breccioid	Recrystallization	Fo, Ph
	Contact hornfels in silica-rich rocks	Kpx+Pl, Q+Ort		Remelting, recrystallization	Kpx, Fa, Ort, Ab
	in dolomites, limestones siliceous and argillaceous dolomites, dolomite marls and anhydrites	Mnt+Fo+Sp+ +Per, Fas+ Fo+Sp+Ph, marbles with Fo, Fas, Mnt; Dt+Fo+Ph+Cal, Di+Ph+Gr+Cal+ +Ang		Recrystallization, replacement of calcite and anhydrite by sulphides, and marmorization	Fo, Fas, Gr, Ph
	in calcareous and non-carbonate argillites	Q+Ort+Pl+ +Hip+Bi, Ort+Pl+Cord, Q+Pl+Di		Recrystallization and partial fusion	Hip, Ort, Bi
Regressive	Feldspar metasomatites	Ab+Ort		-	-
	Magnesian metasomatites	Fo+Fas+Sp		Recrystallization	Fo, Fas, Mnt
	Calcareous-magnesian metasomatites	Mnt+Fas, Sp, Mnt+Fo+Sp		Recrystallization, partial replacement	Mnt, Fas, Fo
	Calcareous metasomatites	Kpx+Gr		Recrystallization	Kpx, Gr

The formation of late mineral associations is not accompanied by any significant addition or removal of components and is treated by us as a low-temperature hydrothermal autometamorphic process.

The structure of the ore zone in the deposits and the classification of copper-nickel sulphide ores

The patterns of distribution of different types of sulphide ores and of mineral concentrations within the ore horizons permit us to analyze the general structure of the ore zones in the deposits of the Noril'sk province. The ore zone of the Talnakh group of deposits has the most complex structure; the structure of the ore zone in the Noril'sk I deposit is simpler; and the variety of ore types in the other deposits of that region is still smaller.

One of the main characteristics of the ore zones in deposits of the Noril'sk province is that their structure changes markedly downdip in the stratified intrusions, from the flanges towards their deepest parts or even feeders. Structural characteristics of the ore zones can be examined most thoroughly on the example of the deposits from the Talnakh ore field. The main features of structure in the vertical sections of the ore zone that are variously oriented relative to the flanges of the intrusions, are shown in fig. 12.

The simplest structure has been observed in the remote locales away from the flanges (fig. 12, I and II). These locales contain impregnated ores in picrite and taxite gabbro-dolerites and may also enclose bodies of massive sulphide ores localized mainly in sedimentary-metamorphic rocks. As we move towards the flanges of the intrusion, the structure of the ore zone grows more complex (fig. 12, III). In addition to the two types of mineral concentrations mentioned earlier, there develop veinlet-impregnated ores in the exocontacts of massive ore deposits.

The locales of the ore zone confined to the flanges of the intrusions have the most complex structure (fig. 12, IV and V): they contain ores of every type. Depending on the geological-

structural conditions of ore deposition, the upper exocontact of the intrusion may enclose veinlet-impregnated mineral concentrations or even massive ores. In magmatic rocks impregnated r.60
ores are found in the horizons of picrite and taxite gabbro-dolerites, but whereas the latter invariably contain mineral concentrations, picrites may be devoid of ore. In isolated apophyses of intrusions, where picrite differentiates are omitted from the section, ores may be found in olivine or taxite gabbro-dolerites. The horizon of massive ores commonly has a complex structure in that part of the ore zone. Sulphide deposits are localized in sedimentary-metamorphic beds, as well as in intrusive rocks. Veinlet-impregnated mineral concentrations occur in metamorphosed sedimentary rocks and are just as extensively developed in the endocontacts of the intrusions. Highly characteristic formations in the flanges of the ore zone are breccioid ores and massive ores associated with them.

At the Noril'sk I deposit all the types of ores are found only in the flanges of the ore zone. In its northern flange there have been encountered ores impregnated in intrusive rocks and veins of massive sulphides localized in sedimentary-metamorphic and extrusive beds, as well as in intrusive rocks; there have also been identified there mineral concentrations of the breccioid type. Impregnated ores are highly characteristic of the extrusive rocks underlying the intrusion. Down the dip of the intrusive massif, in the direction of the presumed magma feeder, the ore zone contains mainly impregnated ores, since bodies of massive sulphides sharply decrease there in number, and concentrations of minerals in the exocontact decline.

Similar characteristics have been recorded at other deposits. It is important to emphasize that at all the deposits isolated bodies of massive sulphides and veinlet-impregnated mineral concentrations have been encountered only in the flanges of the ore zone and are commonly lacking in the plunging parts of the intrusions.

Fig. 12

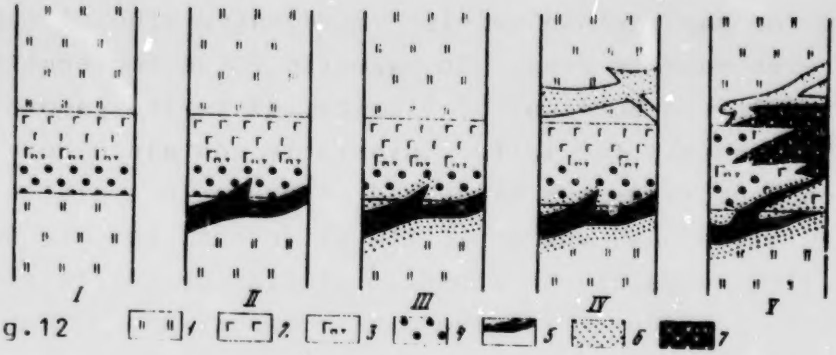

Fig.12

Diagrammatic representation of the structure of the ore zones at the Noril'sk deposits. Descriptions are given in the text. 1-Contact-metamorphic and metasomatic rocks; 2-Diorites, gabbros, olivine-free and olivine gabbro-dolerites; 3-Picrite and taxite gabbro-dolerites; 4-7---Types of ore: 4-Impregnated; 5-Massive; 6-Veinlet-impregnated; 7-Breccioid.

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Fig. 13

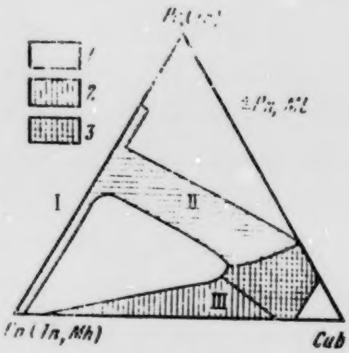

Diagram showing the quantitative mineral composition of the copper-nickel ores from the Noril'sk region.
The main series of variations in the mineral composition of the ores: I-From pyrrhotite to chalcopyrite ores; II-From pyrrhotite to cubanite ores; III-From cubanite to talnakhite (mooihoeckite) ores; 1-3---Compositional fields (areas): 1-With tetragonal chalcopyrite; 2-With talnakhite, mooihoeckite; 3-With tetragonal chalcopyrite and mooihoeckite.

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TABLE 12

Types and mineral varieties of ores from the deposits of the Noril'sk province

Types of ores	Mineral varieties of ores
I. Impregnated ores in differentiated intrusions	
Ia. Impregnated ores in picrite gabbro-dolerites	Chalcopyrite-pyrrhotite, cubanite-chalcopyrite-troilite-pyrrhotite and cubanite-chalcopyrite (talnakhite, mooihoeckite)-troilite ores
Ib. Impregnated ores in taxite gabbro-dolerites	Chalcopyrite-pyrrhotite and pyrrhotite-chalcopyrite ores
II. Massive ores in endo- and exocontacts of stratified intrusions	Pyrrhotite, cubanite, talnakhite, mooihoeckite and chalcopyrite ores
III. Veinlet-impregnated and breccioid ores in endocontacts and exocontacts of stratified intrusions	
IIIa. Veinlet-impregnated ores in metamorphosed rocks from exocontacts of intrusions	Pyrrhotite, pyrrhotite-chalcopyrite, chalcopyrite, millerite-chalcopyrite, bornite, magnetite-pyrite and valleriite-magnetite ores
IIIb. Breccioid ores from exocontact zones in the flanges of intrusions	Pyrrhotite, pyrrhotite-chalcopyrite and chalcopyrite ores
IIIc. Impregnated (sideronitic) ores in olivine gabbro-dolerites from the lower endocontact of intrusions	Pyrrhotite, cubanite, chalcopyrite, talnakhite, Mooihoeckite and bornite ores

Variations in the mineral composition of the ores from different horizons are among the important structural characteristics of the ore zone at ore deposits. These variations reflect the increased structural complexity of the ore zone towards the flanges of the intrusions and the concomitant increase in the number of the mineral associations composing the ore on the one hand, and the development of spatial zoning in their distribution on the other. The most complete zoning has been recorded in deposits of the Talnakh ore field.

Variations of the mineral composition within each particular type of ores manifest themselves in varying proportions of the essential ore-forming sulphides, i.e. pyrrhotites, troilite and minerals of the group of chalcopyrite and cubanite, as well as of some less widely distributed minerals, such as bornite, millerite, pyrite and valleriite.

The main patterns of variations in the ratios of ore-forming sulphides are shown in the diagram (fig. 13) for the most wide-spread ores.

In the diagram the compositions of the ores form three relatively narrow fields corresponding to the series of progressive changes in the proportions of the essential ore-forming minerals. One of the series unites the ores with varying contents of pyrrhotite and tetragonal chalcopyrite. The two other series show variations in the quantitative ratios of cubanite and pyrrhotite or troilite, cubanite and minerals of the group of chalcopyrite (tetragonal chalcopyrite, talnakhite and mooihoeckite). The compositions of the end members in each of the series correspond to the ores in which cubanite, pyrrhotite (± troilite) or minerals of the chalcopyrite group predominate. The systematic variations in the quantitative ratios of the essential ore-forming minerals are the criteria on which the classification of the copper-nickel sulphide ores from the Noril'sk deposits is based (Table 12). In each of the three textural-structural (fabric) types of ores there have been identified the essential mineral varieties corresponding to the compositions of the end members in each series. Since different mineral varieties are linked by gradual uninterrupted transitions, we distinguished several transitional varieties comprising almost equal amounts of two or three ore minerals, in addition to the essential varieties.

CHAPTER 2

p.62

MINERALOGY OF THE NORIL'SK COPPER-NICKEL ORES

The ores of the Noril'sk deposits are unique on account of their mineralogical diversity reflecting the multi-component composition of the primary mineral material and great variations in the geological and physico-chemical conditions of ore emplacement.

The ores from Noril'sk are similar in mineral composition to the ores from the other copper-nickel deposits in the world, but because of their unusually large number of constituent mineral species and widely variable chemical composition, they differ markedly from these ores.

According to the data obtained by the authors and to the literary sources, the Noril'sk ores contain over 100 hypogene ore minerals, among which twenty-six are new mineral species or varieties and fifteen were identified for the first time in the Soviet Union (Table 13). Almost all the known main classes of hypogene ore minerals, from native elements to sulphide hydroxides, have been identified in the Noril'sk ores. The principal components of the Noril'sk ore minerals, the contents of which amount to over 1%, are represented by over 30 elements. p.63

The sequence in which we examine the minerals is based on their abundance in the ores and, partly, on their composition. The minerals are divided into four groups: a) The essential minerals present in the largest quantities in all the types of the ores; b) The accessory minerals identified in many types of the ores, but present in considerably smaller amounts than the essential minerals; 3) The rare minerals found only in some types of the ores and present in small quantities; and 4) The minerals of noble metals (see Table 13).

Because of the multitude of these ore minerals, it is impossible to describe each one of them in detail. For most of the minerals we therefore provide only brief information pertaining to their occurrence in the ores, distinctive aspects of their properties and composition.

TABLE 13

Ore-forming minerals of the Noril'sk ores

Minerals	Names of the minerals
Essential	Minerals of the pyrrhotite group; pyrrhotite hexagonal, pyrrhotite monoclinic, troilite. Pentlandite. Minerals of the group of chalcopyrite: chalcopyrite tetragonal, talnakhite*, mooihoekite**, chalcopyrite cubic***, abnormally anisotropic cubic chalcopyrite***, ferruginous chalcopyrite. Cubanite. Magnetite.
Accessory	Bornite, mackinawite, marcasite, millerite, nickel, pap pyrite, polydymite, sphalerite, tochilinite, chalcosine (chalcocite), heazlewoodite
Rare	Alabandite, altaite, argentopentlandite, breithauptite, violarite, galenoclausthalite, hauchecornite**, gersdorfite, godlevskite*, djerfisherite**, nickeloan (Ni^{2+}) djerfisherite, cassiterite, clausthalite, covellite, loellingite, maucherite, cuproan (Cu^{+}) pentlandite, native copper, molybdenite, native antimony, nickeline, parkerite, perovskite, pyrophanite, rammelsbergite, safflorite, stannite, talkusite*,1/, tetrahedrite, ullmannite, hawleyite, shadlunite*, manganoan (Mn^{2+}) shadlunite
Minerals of noble metals	Argentocuproaurite*, platinian (Pt) atokite, braggite, vincentite**, vysotskite*, geversite**, hessite, zvyagintsevite*, native gold, insizwaite**, kotulskite, cooperite, palladian (Pd) cuproauride, küstelite, michenerite, maslovite*, majakite*, merenskyite**, mertieite II**, moncheite, niggliite, palladoarsenide*, paolovite*, plumbopalladinite*,

polarite*, palladian rustenburgite, native silver, sobolevskite*, sperrylite, stannopalladinite*, stibiopalladinite**; Ag, Cu, Pb sulphosalt, telargpalite*, urvantsevite*, ferroplatinum, froodite**, hollingworthite**, stromeyerite, electrum, (Au, Pd)Cu****, Pd_5As_2, $(Pd, Ni)_5As_2$, $Ni_6Pd_2As_3$, $Pd_2(Sn, Sb)$, $Pd_2(Sn, As)$, $Pd_2(As, Sn)$, (Pd, Pt), $(Sn, As, Sb)_2$, Pd_5Sn_2Cu, Pd_2SnCu, $Pd_5(Sb, As)_2$, (Pd, Pt) (Pb, Bi)(S, Se)

FOOTNOTE:

* New minerals.

** Minerals discovered originally in the USSR.

*** In accordance with the 1979 resolution of the International Commission on New Minerals and Mineral names, IMA, these minerals are now referred to as putoranite and nickeloan putoranite, respectively.

**** Inadequately studied minerals are designated only by formulas.

1/ Transliteration. Translator.

ESSENTIAL ORE MINERALS

Minerals of the pyrrhotite group

A vast literature is devoted to studies of the pyrrhotite group minerals. Among the natural and synthetic sulphides of iron from that group we distinguish at present hexagonal pyrrhotite of a variable composition and with several polytypes, troilite and monoclinic pyrrhotite [208, 169, 282, 198, 281 and 147].

Occurrence and associations. Members of the pyrrhotite group are the most widely distributed minerals in the Noril'sk ores. They are present as essential ore-forming minerals in all the types of the Noril'sk copper-nickel ores: impregnated ores in intrusive rocks, massive, breccioid and veinlet-impregnated ores in the rocks of the exocontact. All the minerals of that group known in nature, i.e. hexagonal and monoclinic pyrrhotite and troilite, have been identified in these ores.

Hexagonal pyrrhotite is developed most extensively in these ores and is absent only from their veinlet-impregnated exocontact type. In the ores, where pyrrhotite predominates, it is represented by two morphological varieties of grains customarily referred to in the literature as pyrrhotite I and pyrrhotite II.

Pyrrhotite I is composed of grains measuring 0.3mm (impregnated ores) to 3-5cm (massive ores). In isolated loci of massive pyrrhotite ores the grains of pyrrhotite I attain 10cm in size, which is a feature specific of the Noril'sk ores. Pyrrhotite I grains have a clearly defined basal parting, along which platy crystals of pentlandite, less often of chalcopyrite or magnetite, are arranged. Pyrrhotite I grains exhibit here and there a distinctive twinning with lenticular-lamellar twin crystals appearing sporadically among them.

Pyrrhotite II differs sharply from pyrrhotite I in the size of grains, crystal structure and distribution in space. Pyrrhotite II grains measure 0.1mm or less. Allotriomorphic-granular aggregates of pyrrhotite II are arranged along the periphery of large pyrrhotite I grains, at their boundary with pentlandite and chalcopyrite or amidst the crystals of the latter. In contrast to pyrrhotite I, it contains no pentlandite or only minutest isometric pentlandite crystals. Pyrrhotite II may be present in chalcopyrite in the form of platy crystals.

Hexagonal pyrrhotite occurs in the ores in the form of homogeneous grains or of intergrowths with troilite and monoclinic pyrrhotite. The intergrowths have been observed in both pyrrhotite I and pyrrhotite II.

Intergrowths of hexagonal pyrrhotite with troilite are widely distributed in impregnated and massive ores. Troilite forms slender lamellar, lenticular or curved vermiform crystals in pyrrhotite (Table V,a) that are subparallel to the basal parting of the latter. The pyrrhotite to troilite ratios vary within a wide range, and in some places troilite is the predominant mineral. The lamellas of troilite increase in size and number towards the periphery of the grains or around the cracks, where they merge changing to continuous borders forming uneven boundaries with pyrrhotite. The troilite-pyrrhotite intergrowths form on account of subsolidus alterations and unmixing of an iron-rich monosulphide solid solution (Mss) at temperatures below 150°C [170, 281]. p.64

Intergrowths of hexagonal and monoclinic pyrrhotite are very frequently encountered in the ores. In polished sections, under the microscope, these pyrrhotite modifications are indistinguishable from one another, and monoclinic pyrrhotite is identified with the help of the magnetic powder method [52]. Monoclinic pyrrhotite develops in hexagonal pyrrhotite mainly in the cracks along the basal parting of the latter and in the periphery of its grains. They are found in widely varying proportions in the intergrowths. When monoclinic pyrrhotite is present in small quantities, it forms thin fringes around the flames and platy crystals of pentlandite and is invariably found along the borders of pentlandite at the boundary of hexagonal pyrrhotite and chalcopyrite grains. There have also been observed intergrowths, in which monoclinic pyrrhotite predominates, while hexagonal pyrrhotite forms isolated irregularly shaped loci (Table V, b).

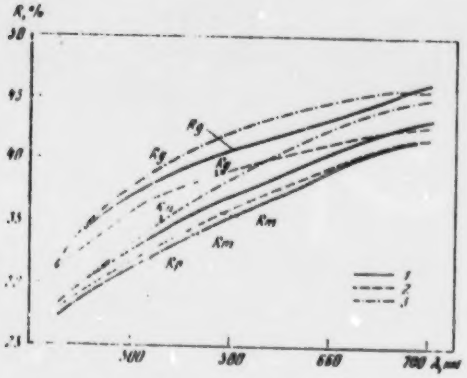
Troilite is represented in the ores by homogeneous grains and by intergrowths with hexagonal pyrrhotite. Homogeneous troilite has been encountered in impregnated and massive ores, where it commonly occurs in association with cubanite, talnakhite and mooihoekite. Large grains of troilite measuring up to 1cm, are surrounded in massive ores by fringes and intersected by veinlets of cubanite. In intergrowths with talnakhite and cubanite or with mooihoekite and cubanite, troilite has been observed amidst the aggregates of these minerals only in the form of relict patches. It is highly characteristic that in homogeneous troilite there are no platy pentlandite crystals along the parting cracks, and pentlandite occurs in it only occasionally in the form of isolated grains.

Monoclinic pyrrhotite has been encountered in all the ore types, but is developed most extensively in breccioid and veinlet-impregnated exocontact ores, where there are virtually no other minerals of the pyrrhotite group. In massive ores it is considerably less abundant than hexagonal pyrrhotite. In the ores composed of homogeneous monoclinic pyrrhotite, monoclinic, as well as hexagonal pyrrhotite form aggregates of large grains with platy inclusions of pentlandite, chalcopyrite and magnetite, and smaller, sometimes lamellar agglomerations amidst chalcopyrite. Platy crystals of monoclinic pyrrhotite in chalcopyrite (Table V, c) are highly characteristic of breccioid ores, but have also been observed in chalcopyrite of the ores impregnated in gabbro-dolerites.

Unlike hexagonal pyrrhotite or troilite, the monoclinic variety of pyrrhotite may exhibit in sections a finely platy texture perpendicular to the basal parting. In polished sections, following the introduction of the magnetic suspension, there appear powder patterns and domain structures that vary in configuration depending on the orientation of the pyrrhotite grains [52, 25] (plate V, d).

The homogeneous monoclinic pyrrhotite found in impregnated ores is predominantly confined in intrusions to the horizon of taxite gabbro-dolerites. In picrite gabbro-dolerites it occurs only in small loci, and in massive ores it has been observed mainly in the parts of the ore deposits adjoining the roof. Intensively disturbed locales of the ore deposits may be completely composed of monoclinic pyrrhotite. p.65

Fig. 14



Reflection spectra of monoclinic (1) and hexagonal (2) pyrrhotites and of troilite (3) after [16].

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In addition to the intergrowths of monoclinic and hexagonal pyrrhotites mentioned earlier, there have been observed in impregnated ores from intrusive rocks trimineral intergrowths composed of monoclinic and hexagonal pyrrhotites and troilite. The outer part of these sulphide agglomerations is composed of monoclinic pyrrhotite; a thin zone of hexagonal pyrrhotite comes next; and troilite occupies the centre.

Composition and properties. Hexagonal and monoclinic pyrrhotite varieties and troilite differ little with regard to their magnitudes of reflectance, but can nevertheless be distinguished from one another on the basis of full reflection spectra (fig. 14). Troilite has the highest reflection* and is therefore invariably of a lighter colour in freshly polished microsections of hexagonal pyrrhotite-troilite intergrowths.

The composition of the pyrrhotite group minerals was determined with the help of an X-ray micro-analyser (Table 14) and by way of X-ray studies from the size of the interplanar distances (d) of reflection (102) [169 and 170]. The values of d_{102} were obtained by the diffractometric method (URS-50-IM**, radiation FeK_a, precision ±0.005 Å) and with the help of debyeograms (URS**-55, Fe, RKD**-57.3mm). We succeeded in obtaining the most accurate ratios of iron and sulphur, the principal components of these minerals, by the diffractometric method.

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* Throughout this work the authors often use the term "reflection" instead of "reflectance" (R). Translator.

** Transliteration. Translator

TABLE 14

Composition of pyrrhotite group minerals (weight per cent, X-ray microanalysis)

Type of ores	Modification	Fe	Ni	S	Total	Me, at. %
Impregnated	M	59.6	0.28	39.4	99.3	46.59
Impregnated	H	61.4	0.35	38.90	100.05	47.68
Impregnated	H+T	61.3	0.07	37.8	99.2	48.24
" " " "	T	63.0	-	36.5	99.5	49.99
Massive	M	59.10	0.46	38.9	98.4	46.77
" " "	H	59.40	0.6	37.8	97.9	47.65
" " "	H	59.50	0.70	38.60	98.80	47.43
" " "	H	60.60	0.60	39.30	100.50	47.85
" " "	H	59.9	0.33	37.9	98.1	47.70
" " "	H+T	61.0	0.08	38.60	99.60	47.81
" " "	T	62.40	-	36.50	98.90	49.76
" " "	T	63.50	-	36.60	100.10	48.89
" " "	T	63.40	0.01	36.70	100.10	49.81
" " "	T	63.10	-	36.50	99.60	50.03
Breccioid	M	59.70	0.60	39.8	100.10	46.51
Veinlet-impregnated	M	56.70	2.60	39.8	98.30	46.55
" " " " " " "	M	58.20	0.56	38.40	97.20	46.76

FOOTNOTE: Here and in Table 15 M stands for monoclinic pyrrhotite, H for hexagonal pyrrhotite, H+T for hexagonal pyrrhotite intergrown with troilite, and T for troilite.

The data obtained from over 140 X-ray diffraction analyses show that hexagonal pyrrhotite has the largest range of compositional variations. The d_{102} values vary within the limits of 2.062-2.077, which corresponds to the contents of metals ranging from 47.0 to 48.3. It has been established that the composition of hexagonal pyrrhotite varies systematically depending on the composition of the minerals associated with it. p.66

The hexagonal pyrrhotite found in intergrowths with troilite has the highest contents of iron (Table 15). The minimum value of d_{102}=2.073 corresponds to 47.9 at. % Me. It is characteristic that the mineral associated with ferroan pyrrhotite is pentlandite with an increased content of iron (up to

35.%Fe). Homogeneous hexagonal pyrrhotite varies in composition within a large range. The pentlandite associated with it has lower contents of iron. The hexagonal pyrrhotite coexisting in intergrowths with monoclinic pyrrhotite, has the highest sulphur concentrations.

TABLE 15

Values of d_{102} for hexagonal pyrrhotites according to X-ray diffraction data.

Hexagonal pyrrhotite	Number of analyses	d_{102}	Me, at. %
H	77	2.063-2.077	47.2-48.3
H + M	43	2.062-2.070	47.0-47.7
H + Tr	21	2.073-2.077	47.9-48.3

According to the data of X-ray diffractometry, troilite has d_{102} values ranging from 2.093 to 2.098. It should be noted that these d_{102} values are greater than the figures 1.0932$\pm$0.001 quoted by P. Toulmin and P. Barton [282] for stoichiometric FeS. Troilite with d^{102}=2.0954 was identified by A.Vorma [286], who believes that the higher d_{102} value of troilite is related to its increased content of iron ($Fe_{1.015}S$) relative to that of stoichiometric FeS. So far there is, however, no experimental evidence in support of that hypothesis.

The existence in nature of troilites with increased contents of iron may be inferred from the fact that d_{102}=2.094 - 2.098 values have been determined only in troilites of impregnated ores from intrusive gabbro-dolerites, whereas the troilites from massive ores analysed under the same conditions and with the help of the same equipment, have d_{102} values that do not exceed 2.093-2.094.

Monoclinic pyrrhotite is characterized by very small variations in composition ranging from 46.5 to 46.75 at.% Me.

Results from determinations of the composition of pyrrhotites with the help of an electron-probe (see Table 14) corroborate the patterns established by the X-ray studies, even though the absolute values of Me/S ratios differ somewhat from the figures obtained by the roentgenometric method.

The data outlined above on the composition of the pyrrhotite group minerals and on the patterns of intergrowth of these minerals in the ores agree with the phase diagram of the Fe-S system (fig. 15). The composition of the minerals and their ratios within the intergrowths are determined by the composition of the primary monosulphide solid solution. Subsequent to its alteration in the subsolidus and depending on the position of the compositional points in the diagram we observed either homogeneous minerals of the pyrrhotite group or mineral intergrowths.

Monoclinic pyrrhotite may also arise as a result of the alteration of a sulphur-rich Mss at 325°C. This appears to be the way in which the monoclinic pyrrhotites from taxite gabbro-dolerites and exocontact ores originated. There are, however, other ways in which monoclinic pyrrhotite may arise. It has been suggested that monoclinic pyrrhotite may form as a result of a low-temperature alteration of hexagonal pyrrhotite, from which a portion of iron atoms has been leached out [25]. Monoclinic pyrrhotite may have arisen in this manner in some locales (particularly in disturbed ones) of massive ore deposits and in isolated irregularly distributed loci of impregnated ores in picrite gabbro-dolerites. The intergrowths of these minerals in impregnated ores that were mentioned p.67 earlier, and the fringes of hexagonal pyrrhotite bounding the cracks in troilite that have been observed in some places in massive ores, evidence that monoclinic and hexagonal pyrrhotites form by way of the diffusive removal of iron from troilite. Monoclinic pyrrhotite may also crystallize directly from solutions as the primary phase. The small platy crystals arising in the ores impregnated in picrite gabbro-dolerites as a result of the serpentinization of olivine, may be among the relatively rare instances when monoclinic pyrrhotite forms this way.

The most characteristic trace element of the Noril'sk pyrrhotites is nickel (see Table 14). Monoclinic pyrrhotite from exocontact ores has the highest content of nickel. In veinlet-impregnated ores the concentration of nickel attains 2.6%. The contents of nickel quoted in the literature [260, 284. 207, 220, 246, 156 and 157] are lower except for the pyrrhotite with 3.2 wt % Ni mentioned by N.Page [259].

It has been established that the content of nickel in the pyrrhotite group minerals varies in a systematic manner in the solid solution. Significant variations in the concentration of nickel have been revealed in hexagonal pyrrhotite as a function of its paragenesis. The ferroan hexagonal pyrrhotites coexisting with troilite have the lowest nickel concentrations (0.02-0.20%). Concentrations of nickel in homogeneous hexagonal pyrrhotite in the solid solution are 0.30-0.70%, but attain 0.75-0.80% in the hexagonal pyrrhotite coexisting with microclinic pyrrhotite.

Nickel contents in troilite are 0.03% or less. Analyses with the sensitivity threshold below 0.01% detected no nickel at all in many of its grains. Nickel concentrations in the troilite intergrown with hexagonal pyrrhotite are for the most part an order lower or nil. Equal contents of nickel (0.01-0.03%) in both minerals have been observed very rarely.

Of great interest are the patterns of the distribution of nickel between the coexisting monoclinic and hexagonal pyrrhotites. There have been established two types of nickel distribution in these minerals.

Fig. 15

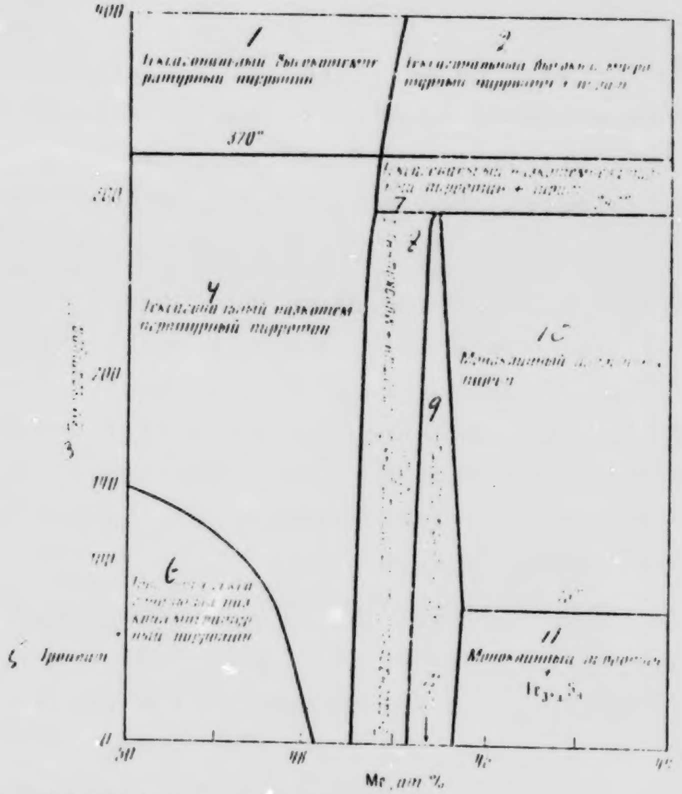
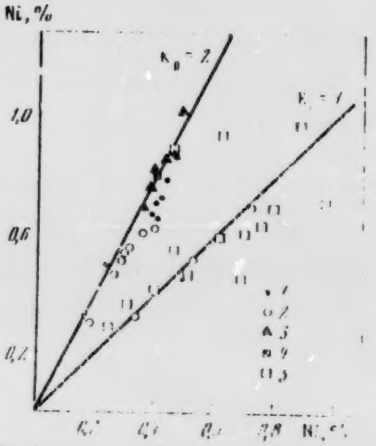


Diagram of the Fe-S system after [28].
1-Hexagonal high-temperature pyrrhotite; 2-Hexagonal high-temperature pyrrhotite+pyrite; 3-Temperature °C; 4-Hexagonal low-temperature pyrrhotite; 5-Troilite; 6-Troilite and hexagonal low-temperature pyrrhotite; 7-Hexagonal low-temperature pyrrhotite+pyrite; 8-Hexagonal low-temperature pyrrhotite+monoclinic pyrrhotite; 9-Monoclinic pyrrhotite; 10-Monoclinic pyrrhotite; 11-Monoclinic pyrrhotite.

Fig. 16



p.68

Distribution of nickel in coexisting hexagonal (Y-axis) and monoclinic (X-axis) pyrrhotites.

Nickel distribution coefficients:
1-Data of the authors; 2-After [157]; 3-After [284]; 4-After [172]; 5-After [246].

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In most of the pyrrhotite intergrowths analysed from massive ores the content of nickel in hexagonal pyrrhotite is nearly twice its concentration in monoclinic pyrrhotite. These ratios were already mentioned earlier [284, 172 and 149].

The second type of distribution with equal concentrations of nickel in the two coexisting pyrrhotite varieties has been observed in impregnated and massive ores [157 and 246]. Both types of distribution are shown in fig. 16 on the basis of our data and those found in the literature.

The content of nickel in homogeneous monoclinic pyrrhotite is commonly 0.4-0.8 wt %, but is up to 1.6 wt % in impregnated and 2.6 wt % in exocontact ores.

The equal fractionation of nickel between the coexisting hexagonal and monoclinic pyrrhotites and the high contents of nickel in monoclinic pyrrhotites of impregnated and exocontact ores appear to be characteristic of the pyrrhotites evolved as a result of subsolidus alterations of a sulphur-rich Mss. This has been corroborated by the results of the experimental studies carried out by A. Naldrett and J. Craig [250], who established that the concentration of nickel in Mss increases as its content of sulphur rises.

The coefficient of nickel distribution in pyrrhotites equal to 2 can probably be realized more readily when monoclinic pyrrhotite substitutes for hexagonal pyrrhotite with removal from the latter of iron and nickel.

The information available on the contents of cobalt in pyrrhotites from Noril'sk is considerably more sketchy and less reliable [156 and 157]. Minor copper contents (0.01-0.03% or less) have been established in many pyrrhotites with the help of an electron-probe. Troilite fringes containing up to 0.5% copper have been detected in agglomerations* of troilite from massive ores, along the cracks and in the periphery of these agglomerations at their contact with cubanite [84].

Alterations of pyrrhotite. The most typical alteration of pyrrhotite is its replacement by pyrite or nickeloan pyrite. This phenomenon becomes progressively more wide-spread in the impregnated-massive-exocontact series of ores. In impregnated ores pyrite occurs sporadically amidst pyrrhotite in the form of metacrysts or small aggregates and is almost always represented there by its monoclinic modification. Intensive replacement of pyrrhotite by pyrite in massive ores has been observed only in the parts of the deposits located near tectonic disturbances. The pyrite or nickeloan pyrite developing in pyrrhotite may be closely intergrown with magnetite. In exocontact ores, where the processes of replacement occur on a particularly large scale, there have been observed isolated locales of veinlet-impregnated mineral concentrations represented by magnetite-pyrite ores. Replacement of pyrrhotite by aggregates of minerals from the valleriite-tochilinite group is also a wide-spread phenomenon in these ores.

Pentlandite

p.69

Pentlandite is widely distributed in the ores of copper-nickel deposits. The vast literature dealing with pentlandite has been summarized by O.Knop et al. [236]. In subsequent years there appeared a large number of publications devoted to experimental studies of pentlandite and its position in the Fe-Ni-S system [124, 250, 272, 47, 106, 196 and 246] and to electron-probe studies of the composition of pentlandite and of the conditions under which it occurs [251, 260, 33, 154, 207, 220, 259, 115, 246 and 116].

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* The Russian term used "vydelenie" means a discrete mass or body formed as a result of seggregation, precipitation, isolation, crystallization, emanation, emission, etc. In some cases it obviously stands for "crystal", but in others the nature of the mass or body referred to is not clear, and it has been translated as "agglomeration". Translator.

The crystal structure of pentlandite was deciphered more than forty years ago [239]. The face-centered-cubic unit cell of pentlandite contains 32 sulphur atoms and 36 atoms of metals arranged in tetrahedral (32) and octahedral (4) positions. The possibility of disposing the atoms of metals (Fe, Ni, Co, Cu, Ag) in different positions within the structure of pentlandite accounts for the variations in the composition of pentlandite and for the existence of structural analogues of that mineral (argentopentlandite and cuproan pertlandite).

Occurrence and associations. Pentlandite is the most widely distributed mineral of the Noril'sk ores. The development of pentlandite in the ores is controlled mainly by the mineral composition of these ores, which accounts for the presence of similar morphological varieties of that mineral in analogous mineral associations of pentlandite from the main (massive, impregnated, veinlet-impregnated and breccioid) types of ores.

In its most wide-spread association with pyrrhotite and chalcopyrite (pyrrhotite ores) pentlandite is commonly represented by small (0.01 X 0.1mm) platy crystals or flames in pyrrhotite grains and by fringes (0.1-0.4mm in width) along the pyrrhotite-chalcopyrite boundary. The platy crystals and flames are arranged parallel to the parting (0001) or pyrrhotite; moreover, the latter are found for the most part around small cracks in pyrrhotite. In sections of pyrrhotite grains parallel to (0001) the platy crystals are shaped in the form of radial-dendritic rosettes (Plate VI,a). The arrangement of pentlandite lamellas may be tridirectional. When pentlandite occurs in the form of slender fringes along the boundaries of pyrrhotite grains, there are no pentlandite lamellas near these borders (Plate VI,b). The fringes and crystals of pentlandite disposed inbetween the pyrrhotite grains, have been encountered in the locales of massive pyrrhotite ores that contain large quantities of embayed silicate particles and are represented by a fine-grained pyrrhotite (Plate VI,c).

Isometric pentlandite crystals measuring about 1mm and confined to the boundary of pyrrhotite with chalcopyrite, are found in this association in lesser quantities. It has been observed that pentlandite crystals increase to 3-5mm in massive pyrrhotite ores near the locales, where pentlandite is associated with troilite and cubanite.

Porphyroid crystals of pentlandite (up to 1.5cm in size) have been encountered much more frequently in association with the predominant minerals cubanite and troilite (troilite-cubanite or chalcopyrite-cubanite ores). Furthermore, pentlandite is extensively developed in that association in the form of aggregates of small crystals occurring largely amidst cubanite. In contrast to pyrrhotite, troilite commonly contains no small inclusions or flames of pentlandite.

The most typical grain shape of the pentlandite associated with the chalcopyrite group minerals predominating in the ores (chalcopyrite, talnakhite and mooihoekite), is spherical, oval, regularly isometric or irregular. In impregnated ores its grains measure 3-5mm or less, but in exocontact veinlet-impregnated or breccioid ores they may be up to 10mm. The largest crystals (up to 3cm) are characteristic of chalcopyrite and mooihoekite ores (Plate VI, d). Minerals of the chalcopyrite group may occur in porphyroid grains of pentlandite in the form of veinlets forming a sort of lattice (meshwork) along the cleavage of p.70 pentlandite. In some places these minerals replace pentlandite and form typical veinlets cutting across its crystals. In addition to occurring in large agglomerations, pentlandite is found in association with talnakhite and mooihoekite in the form of veinlet-like tabular crystals that are variously oriented depending on the orientation of the host mineral's grains.

Large pentlandite crystals occur in association with chalcopyrite-bornite or bornite which often composes the contact-line locales in ore deposits or forms discrete veinlets. Peculiar graphic structures may develop in pentlandite at the contact with bornite as a result of its replacement by bornite.

Pentlandite has also been observed in association with less common minerals. It forms fringes around alabandite veinlets in massive mooihoekite ores and along the boundaries of pyrrhotite and nickeloan djerfisherite in exocontact veinlet-impregnated ores. Minutest pentlandite crystals overgrow reniform breithauptite-nickeline aggregates in carbonate veins amidst massive pyrrhotite ores. The formation of pentlandite in these associations may be related to the redeposition of earlier generations of that mineral.

The composition of pentlandite. A characteristic feature of pentlandite from the Noril'sk ores is its large range of compositional variations, larger than at any other deposits of copper-nickel ores. It has been established that the range of variations of its principal components is as follows (weight %): 25.0-46.0 Ni, 21.0-41.0 Fe, 0.3-4.7 Co and 0-0.6 Cu.

The variations in the composition of pentlandite systematically related to the succession of its associations in the ores (Table 16) are most clearly pronounced with regard to the contents of nickel. In pyrrhotite varieties of all the ore types they vary within the relatively small interval of 34 to 38%; moreover, the maximum nickel concentrations have been recorded in the pentlandite associated with monoclinic pyrrhotite. It should be noted that different morphological varieties of pentlandite (flames and platy crystals, fringes etc.) have the same composition in associations of pentlandite with pyrrhotite or other minerals. This fact has already been noted in the literature [116]. p.71

The content of nickel decreases markedly in the pentlandite associated with hexagonal pyrrhotite and troilite and amounts to 31-33% Ni; in the pentlandite associated with homogeneous troilite and cubanite it is already 28-30%; and the lowest nickel concentrations have been recorded in the pentlandite associated with talnakhite and mooihoekite, where it ranges from 25 to 30%.

TABLE 16

Composition of pentlandite from the Noril'sk copper-nickel ores (weight %, X-ray micro-analysis)

Types of ores	Associations of pentlandite	Ni	Fe	Co	Cu	S	Total
Impregnated ores in intrusions of gabbro-dolerites	Po_m+Cp	37.0	28.2	1.8	-	32.7	99.7
	Po_m+Po_n+Cp	36.2	29.7	1.5	-	32.9	100.3
	Po_n+Cp	35.1	30.6	1.4	-	32.0	99.1
	Po_n+Cp+Cub	34.6	31.6	1.0	-	32.5	99.7
	Po_n+Tr+Cp+Cub	32.1	34.5	1.0	-	33.1	100.7
	Tr+Mh+Cub	28.8	37.3	0.9	-	33.8	100.8
Massive ores	Po_m+Cp	37.3	28.2	1.9	-	33.2	100.6
	Po_m+Po_n+Cp	36.0	28.7	2.1	-	33.1	99.9
	Po_n+Cp	35.5	29.7	1.7	-	33.0	99.9
	Tr+Po_n+Cp+Cub	32.6	33.6	1.2	-	33.0	100.4
	Cp+Tr+Po_n+Cub	32.3	33.1	1.1	-	33.2	99.7
	Tr+Cub	28.5	38.1	1.0	0.02	33.2	100.82
	Cub+Tn(Mh)	28.8	37.2	0.4	0.5	32.4	99.3
	Mh+Cub	25.0	40.7	0.9	0.1	31.5	98.2
	Cp	37.6	30.0	0.6	-	32.4	100.6
	Bo+Cp	44.6	24.1	0.47	-	32.5	101.6
Veinlet-impregnated and brecciated ores in country rock	Cp	46.6	20.5	1.1	-	31.5	99.7
	Cp+Bo	46.1	20.9	0.7	-	33.0	100.6
	Po_m+Cp	38.0	27.1	1.5	-	33.5	100.1
	Cp+Po_m	37.3	29.4	0.7	-	33.1	100.3
	Cp	38.5	27.1	1.6	-	32.2	99.4
	Cp+Mil	41.6	25.1	0.3	-	32.2	99.2

In pentlandite-chalcopyrite associations, where chalcopyrite predominates (chalcopyrite ores), the content of nickel in pentlandite tends to increase. This tendency is particularly well pronounced in the chalcopyrite veinlet-impregnated exocontact ores, where the contents of nickel are up to 46.6% (Table 16). High nickel concentrations are also characteristic of the pentlandite associated with bornite and millerite.

It has thus been established that variations in the content of nickel in pentlandite form two series depending on the associations of pentlandite: 1) decreasing progressively from the Pn+Po to the Pn+Mh(Tn) associations, and 2) increasing in the Pn+Cp and Pn+Bo associations.

There have also been observed other variations in the composition of the pentlandites with decreasing nickel concentrations: 1) the content of cobalt amounts to 1.3-0.4 in the ores from the Talnakh deposit, but is 2.2-1.0% in the ores of the Oktyabr'skii deposit; and 2) in the pentlandites associated with talnakhite and mooihoekite, there appears copper.

A highly important index of the composition of pentlandites is their Me:S ratio. The content of sulphur in stoichiometric pentlandite (Me_9S_8 - $Fe_{4.5}Ni_{4.5}S_8$) should be 33.05 wt %. As may be seen from Table 16, the concentration of sulphur in the Noril'sk pentlandites varies from 31.5 to 33.8 wt %. The spread of sulphur contents in these pentlandites quoted by G.A. Mitenkov et al. [115 and 116], is even greater (30.1-35.8 wt %), which may be due to the insufficient precision of their analyses. Judging from the data found in the literature, the range of variations in these contents is equally large in pentlandites from other deposits; moreover, according to D. Harris and E. Nickel [220], their Me:S ratio varies concomitantly from $Me_{8.5}S_8$ to $Me_{9.5}S_8$. These authors believe that it is so far an open problem whether these data reflect the real variations of the sulphur content in pentlandite and the deviation of its composition from stoichiometry, or are a result of analytical errors.

The properties of pentlandite as a function of its composition. Because of the variations in the composition of the pentlandites from Noril'sk, their optic properties and, particularly, the size of their unit cells also vary.

It has been established that the reflection coefficient (R) of pentlandites increases as their content of nickel rises.

This correlation is sustained throughout the reflection spectrum of pentlandites. It is illustrated graphically in fig. 17 for the wave length λ=580nm. In spite of some deviations, the general pattern of the increase in R is fairly well defined. As may be seen from the graph, in the pentlandites with the highest nickel concentrations the curve flattens out with the slightest change in R.

The size of the unit cell as a function of the composition has been studied most thoroughly for synthetic pentlandites.

The first data pertaining to the changes of that parameter in pentlandite with changes in its iron and nickel contents were published by D. Lundkvist [240]. In the end members synthetized by him, $Fe_{5.22}Ni_{3.78}S_8$ and $Fe_{3.78}Ni_{5.22}S_8$ stable below 200°C, the size of the unit cell proved to be 10.195Å and 10.095Å, respectively, which testifies that it progressively increases as the content of iron in pentlandite rises.

The data presented by O.Knop, M.Ibrahim and Sutarno [235 and 236], who established this correlation for the whole series of the pentlandites synthetized by them, are more complete. The end values of a are 10.211± 0.002 Å for $Fe_{2.25}Ni_{6.75}S_8$. The curve depicting the dependence of a on the content of nickel is sharply inclined in the iron-rich section, but flattens out in nickeloan pentlandites. The authors plot for comparison the curve for $(Fe,Ni)_8CoS_8$ in the same graph and show that introduction of 7.6 wt % Co reduces a by 0.055Å or less. O.Knop et al. conclude that in natural pentlandites containing commonly 2 wt % Co or less, the effect of cobalt on the size of the unit cell is negligibly small and reduces it by 0.012 Å or less. Of great interest are the data of O.Knop et al. indicating that the unit cell of natural pentlandites is smaller than that of compositionally analogous synthetic pentlandites. p.72

The experimental studies carried out by R.Shewman and L.Clark [272] on phase relations of pentlandite in the Fe-Ni-S system, have corroborated on the whole the findings of O.Knop et al. [236]. These authors constructed a curve (fig. 18) correlating the composition and interplanar distances (d_{115}) of synthetic pentlandites. R.Shewman and L.Clark were the first to present data pertaining to the highly important problem of the Me:S ratio in synthetic pentlandites. They determined the following solubility thresholds of sulphur in pentlandite: 32.5 ±0.2 to 34.0±0.3 wt % (at 600°). Given these variations in the content of sulphur in pentlandite, the interplanar distances d_{115} and a of a pentlandite with Fe:Ni=1:1 will decrease.*

As a result of studying synthetic pentlandites, we have thus been able to determine that the parameters of these pentlandites are generally a function of their iron content and have greater values than those of compositionally similar natural pentlandites. The effect of Me:S has so far been little studied and should be investigated further.

The extensive variations in the composition of the Noril'sk pentlandites (see Table 16) with the contents of nickel varying from 25.0 to 46.0 wt %, account for the large-scale variations in their parameters ranging from 10.18 to 10.03Å. Interplanar distances d_{115} were determined in pentlandites with the help of an URS**-50 I diffractometer (FeK_a- radiation, standard Si) with a precision of ±0.0005 Å.

Comparison of the relation between the unit cell parameters and composition of the Noril'sk and synthetic pentlandites (fig. 18) shows a generally similar tendency of their parameters to decrease as their contents of nickel rise. Among the Noril'sk pentlandites there have, however, been established two different groups. Pentlandites of the first group with nickel concentrations varying from 25.0 to 32.0 wt % and with a equal to 10.18 and 10.11 Å, respectively, are located very close to the curve of synthetic pentlandites and have consequently very similar unit cell parameters to those of the latter. These pentlandites associate p.73

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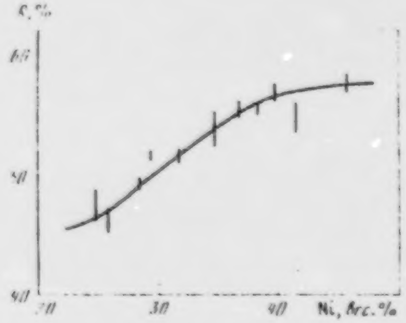
* An obscurely worded sentence in Russian. Translator.

** Transliteration. Translator.

with talnakhite and mooihoekite, sulphur-deficient minerals of the chalcopyrite group. In pentlandites of the second group with 32.0 - 46.0 % Ni and a equal to 10.06-10.03Å, the parameters of the unit cell differ considerably from those of compositionally similar synthetic pentlandites and, as the quantity of nickel increases, they vary along an independent curve.

Fig. 17



Reflectance (R) of pentlandite for λ=580 as a function of its nickel content. Vertical lines show the spread of parallel R determinations.

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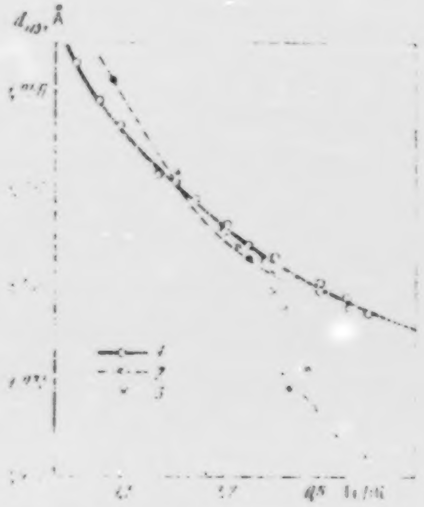
Fig. 18



Interplanar distances of synthetic [272] and Noril'sk pentlandites as a function of their nickel contents.
1-Homogeneous pentlandites with a constant 33.05 S wt% synthetized at 400 or 600°C; 2-3---Noril'sk pentlandites: 2-Data obtained by the authors; 3-After [115].

*****

The data found in the literature [115] show that in nature there may be pentlandites with constant nickel contents of 32 to 35 wt %, but with highly variable parameters of the unit cell. These pentlandites may fill the inflexion region of the curves depicting the parameter as a function of the composition (fig. 18). The unit cell of the ferroan (Fe^{2+}) pentlandites from Noril'sk is close in size to that of the synthetic pentlandites with a constant sulphur content (33.0 wt %), which suggests that both have a stoichiometric composition. The marked drop of the unit cell parameters in the Noril'sk nickeloan pentlandites relative to their synthetic analogues cannot be attributed to the effect of the cobalt contents, since they are even smaller in the pentlandites having the highest cobalt concentrations than in ferroan pentlandite varieties. The decrease may be related to the occupation of all the octaherdal positions by nickel cations with a smaller radius. It is, however, more probable that it is due to the deviation of these pentlandites from stoichiometry during their formation under conditions of a greater fugacity of sulphur.

The patterns established are a typomorphic characteristic of pentlandites and contribute to the clarification of the conditions under which they formed.

Alterations of pentlandite. The alteration of pentlandite, its replacement by mackinawite, occurs on the largest scale in its associations with cubanite and troilite. In associations with cubanite and talnakhite (less often with mooihoekite) pentlandite becomes replaced by cuproan pentlandite. This is a less wide-spread phenomenon that is, however, characteristic of the Noril'sk ores.

There have also been observed other, even more unusual instances of the replacement of pentlandite 1) by djerfisherite along the periphery of its porphyritic phenocrysts associated with cubanite and talnakhite, 2) by argentopentlandite in pyrrhotite-chalcopyrite ores; or 3) by heazlewoodite, godlevskite and millerite in bornite and chalcopyrite-bornite ores.

Replacement of pentlandite by violarite that is a typical phenomenon at other copper-nickel deposits, has been observed at the Noril'sk deposits only in vertical chalcopyrite veins [18].

Pentlandite undergoes the most substantial metamorphic alterations in veinlet-impregnated exocontact millerite-chalcopyrite ores, where it persists only in the form of relicts or becomes completely replaced by millerite+nickeloan pyrite+chalcopyrite, millerite+violarite+nickeloan pyrite or millerite+polydymite aggregates, to which there may be confined here and there small grains of vysotskite.

Chalcopyrite group minerals.

Chalcopyrite is among the most widely distributed copper and iron sulphides in nature and one of the principal ore-forming minerals in copper-nickel ores, alongside pyrrhotite and pentlandite. This mineral has recently attracted a great deal of attention as a result of the discovery of its new varieties important for elucidating the conditions of formation of ores. All the currently known natural and synthetic copper and iron sulphides that are close in composition to chalcopyrite, are presented in Table 17.

The discovery and studies of these minerals have a very interesting history. The cubic modifications of chalcopyrite had not been identified in nature for a long time. The first find of cubic chalcopyrite in copper-nickel ores from the Noril'sk I and Talnakh deposits was reported in 1963 [5]. According to the data of these authors, the mineral has a crystal lattice of the type of sphalerite with the edge of the unit cell a=5.280±0.005 Å. Chemical analyses revealed in it a sulphur deficiency and traces of Ni and Zn. The authors believe this mineral to be a natural analogue of the high-temperature synthetic cubic chalcopyrite [200] and point out that cubic chalcopyrite is widely distributed in the Noril'sk ores and is the essential mineral of these ores in the loci, where its content attains 60-70%. p.74

TABLE 17

Chalcopyrite group minerals

Mineral	Formula	a,Å	b,Å	c,Å	Space Group	z	Author
Tetragonal chalcopyrite	$Cu_8Fe_8S_{16}$	5.289	5.289	10.423	142d	4	214
Talnakhite	$Cu_9(Fe,Ni_8)S_{16}$	10.593	10.593	10.593	143m	16	5, 28 173,215
Mooihoekite	$Cu_9(Fe,Ni)_9S_{16}$	10.58		5.36	P42m	8	178,118, 214,216 217
Haycockite	$Cu_8(Fe,Ni)_{10}S_{16}$	10.705	10.734	31.630	P2*2* 2*	48	178,214 200,173
Cubic, chalcopyrite, synthetic	$CuFeS_2$	5,264			F***	2	
Cubic chalcopyrite	$Cu_{17}(Fe,Ni)_{17}S_{32}$	5.30					150
Abnormally anisotropic chalcopyrite	$Cu_{16}(Fe,Ni)_{19}S_{32}$	5.30					150
Ferroan chalcopyrite	$Cu_{0.90}Fe_{1.14}$ $Ni_{0.01}S_2$	5.30		10.42			83

Studies by A.D. Genkin et al. [28] have shown that cubic chalcopyrite is not always homogeneous, but may be represented by intergrowths of the cubic and tetragonal phases. L. Cabri, who studied the Noril'sk ore samples analysed earlier by I.A. Bud'ko and E.A. Kulagov, has demonstrated that the mineral referred to as cubic chalcopyrite, is not an analogue of synthetic cubic chalcopyrite. In contrast to the latter, it has a cubic body-centered unit cell (a=10.648 Å), a composition close to $Cu_{18}(Fe,Ni)_{18}S_{32}$, and is an analogue of the synthetic beta-phase [173]. This is the mineral designated as talnakhite. L. Cabri and R. Goodman [80] analyzed the Mössbauer spectra of talnakhite; L. Cabri et al. [177] determined more accurately its chemical composition; and S. Hall and E. Gabe [215] established that talnakhite has a cubic structure, space group I $\bar{4}$3m and a=10.593 Å.

Mooihoekite and haycockite, two new copper and iron sulphides similar in composition to chalcopyrite, were discovered in recent years in the samples from a dunite pipe at Mooihoek (Transvaal, South Africa) and from the gabbro complex at Duluth (Minnesota, USA). According to the data of L. Cabri and S. Hall [178], mooihoekite is tetragonal, $a=10.58\,\mathrm{\AA}$, $c=5.47\,\mathrm{\AA}$, space group $P\bar{4}2m$, $d=4.38$ g/cm^3, and is an analogue of the synthetic gamma-phase undersaturated with sulphur, that has a tetragonal unit cell $a=10.58\,\mathrm{\AA}$ and $c=5.37\,\mathrm{\AA}$ [226]. Simultaneously with L. Cabri's discovery this mineral was identified in massive copper-rich ores of the Oktyabr'skii deposit in association with two other minerals of the chalcopyrite group characterized by a cubic primitive unit cell $a=5.30\,\mathrm{\AA}$ [118]. Haycockite is rhombic, pseudotetragonal [266] (Table 17), with $d=4.35$g/cm^3. In reflected light it resembles tetragonal chalcopyrite.

In some of the varieties of massive cubanite ores from the Oktyabr'skii and Talnakh deposits there have been encountered tetragonal chalcopyrites with increased nickel concentrations, in which iron predominates over copper. A.M. Karpenkov and I.S. Rudashevskii [83], who established that the content of nickel in some of the chalcopyrites was up to 1.9 wt %, suggested to designate them as nickeloan chalcopyrites. These authors refer to the chalcopyrites with greater contents of iron than of copper (on an average 3 wt %), as ferroan chalcopyrites. It may thus be seen that with the exception of haycockite, all the known natural minerals of the chalcopyrite group have been identified in the copper-nickel ores of the Noril'sk deposits. p.75

Tetragonal chalcopyrite is the most wide-spread mineral of the chalcopyrite group. It is found as an accessory mineral with a relative content of 10-15% or less, in all the types and mineral varieties of the ores and amounts to 60-80% in the chalcopyrite ores, in which tetragonal chalcopyrite is the essential ore-forming mineral.

In massive pyrrhotite ores the bulk of chalcopyrite occurs in the form of irregular knitted veinlet-like agglomerations a few tens of millimetres to 1-2cm in width, in the interestices between large grains of pyrrhotite. Its uneven boundaries with many embayments in pyrrhotite testify that pyrrhotite I has been corroded and replaced by chalcopyrite. At the same time chalcopyrite is intersected by veinlets of small-grained pyrrhotite II.

Lamellae of chalcopyrite may be observed together with pentlandite along the basal parting in large grains of pyrrhotite I. They may be, similarly to pentlandite, products of unmixing of the pyrrhotite solid solution. Slender veinlets cutting across pyrrhotite, pentlandite and magnetite, are relatively rare.

In the ores impregnated in intrusive rocks chalcopyrite composes isolated parts of insets and is separated from pyrrhotite by fringes of pentlandite. The relative content of chalcopyrite in pyrrhotite varieties of impregnated ores is 10 to 30% of the sulphide mass, and in chalcopyrite ores it is 45 to 70%. In breccioid ores chalcopyrite occurs, as a rule, separately from pyrrhotite; it concentrates mainly in fragments of pyroxene hornfels cemented by pyrrhotite, where it forms thin intergrowths with pyroxene and borders around the fragments. The relative content of chalcopyrite relative to the sulphide mass in the fragments is about 60-85% and in the cement it is 15%.

Tetragonal chalcopyrite is the most abundant mineral in veinlet-impregnated ores from the exocontact of intrusions. Its relative content in the sulphide mass of pyrrhotite ores is 20-30%; in the other ore types chalcopyrite sharply predominates.

Chalcopyrite aggregates have an inequigranular texture with grains measuring 0.1 to 1-2mm. In massive chalcopyrite ores the grains are larger, measuring up to 2-3mm. A characteristic feature of chalcopyrite is its clearly defined anisotropy with twin crystals distinctly observable at crossed nicols. The twins are commonly polysynthetic or have a basket-weave texture. Chalcopyrite may contain inclusions of cubanite which form series of parallel or crossed lamellas with sharp straight boundaries, varying in orientation in different chalcopyrite p.76

grains. Most researchers regard these lamellas as a product of unmixing of the chalcopyrite solid solution. The stellular grains of sphalerite often observed in chalcopyrite from massive chalcopyrite ores, should probably be also referred to that type of inclusions.

TABLE 18

Dispersion of reflection of chalcopyrite group minerals

λ,nm	1	2	3	4	5	λ,nm	1	2	3	4	5
440	19.6	25.3	24.8	27.4	28.9	600	40.0	41.1	42.6	42.7	52.8
460	24.7	28.9	28.3	30.7	33.9	620	40.6	41.5	43.1	44.0	53.1
480	28.8	32.3	31.7	33.5	39.9	640	40.8	42.0	43.1	44.8	53.1
500	31.8	34.9	34.4	36.0	44.5	660	41.3	42.3	43.7	45.8	52.7
520	34.6	37.1	37.2	38.1	47.8	680	41.7	42.2	43.8	46.4	52.2
540	36.7	39.0	39.2	39.5	50.1	700	42.0	42.6	43.9	46.7	51.8
560	38.4	39.9	40.5	41.0	51.8	720	42.0	42.8	43.8	45.5	51.4
580	39.4	40.8	41.9	42.1	52.4	740	42.1	42.6	44.0	45.6	50.9

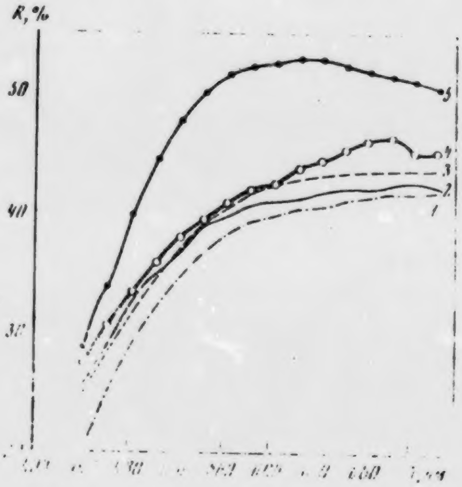
1-Talnakhite; 2-Mooihoekite; 3-Cubic chalcopyrite; 4-Abnormally anisotropic cubic chalcopyrite; 5-Tetragonal chalcopyrite. Chemical composition (wt %) Cu=34.56, Fe=30.52 and S=34.92 wt %.

In cubanite and chalcopyrite-pyrrhotite-cubanite or other transitional varieties of ores chalcopyrite agglomerations are in the form of relict patches identical in internal structure to chalcopyrite aggrega[illegible] from pyrrhotite or chalcopyrite ores.

Tetragonal chalcopyrite has the highest R values throughout the spectrum and the minimal slope of the dispersion curve (fig. 19, Table 18). X-ray powder patterns of chalcopyrite display clearly perceptible lines of tetragonal doublets (1.867-1.853 and 1.590-1.572). The calculated parameters of the unit cell a=5.28 and c=10.40Å correspond to the standard.

Chemical composition of the chalcopyrite from massive and impregnated chalcopyrite-pyrrhotite ores is close to the theoretical composition $CuFeS_2$ (Table 19). In addition to the essential elements it almost invariably contains nickel (0.01 to 0.05 wt %). The chalcopyrites found in relict crystals amidst cubanite ores or chalcopyrite-cubanite and other transitional ore varieties, differ somewhat from the theoretical chalcopyrite. Their content of iron is usually higher than that of copper (the Cu:Fe ratio varies from 1 to 0.89). Another distinctive characteristic of these chalcopyrites is their variable Ni content even within individual grains. Chalcopyrite becomes replaced by valleriite and mackinawite that forms veinlets in chalcopyrite. In some places chalcopyrite is intersected by veinlets of late magnetite.

Fig. 19



Reflection spectra of chalcopyrite group minerals
1-Talnakhite; 2-Mooihoekite; 3-Cubic chalcopyrite; 4-Abnormally anisotropic cubic chalcopyrite; 5-Tetragonal chalcopyrite.

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Talnakhite was initially described in the literature as cubic chalcopyrite [5] and later on as a new copper and iron sulphide [173]. Talnakhite becomes more intensively oxidized in the air than any other mineral of the chalcopyrite group and it therefore sharply contrasts with the other minerals even macroscopically. Under the microscope it is similar in colour and reflection to cubanite and other chalcopyrite group minerals, excepting tetragonal chalcopyrite. Microhardness ($H_{mean}=277$ kG/mm^2) greater than in any of the other minerals from that group.

At deposits of the Noril'sk province talnakhite occurs mainly in massive ores and is found less often as a constituent of sulphide aggregates in ore-bearing intrusions. In these types of ores talnakhite associates with all the minerals of the chalcopyrite group, as well as with cubanite and pentlandite; the association of talnakhite with troilite is highly characteristic of impregnated ores. Massive talnakhite ores contain homogeneous grains of talnakhite, but aggregates, in which talnakhite encloses regularly oriented platy inclusions of tetragonal chalcopyrite, are equally characteristic. These lamellas appear to have formed as a result of unmixing of the solid solution of chalcopyrite (Plate VII,a). p.77

Debyeograms of talnakhite display no doublets of the kind characteristic of tetragonal chalcopyrite (1.853 and 1.590-1.572Å), but the lines with d_a=5.70Å are there clearly perceptible and talnakhite can therefore be readily distinguished from the other cubic phases. Unit cell parameters of talnakhite show good agreement with the data of L.Cabri [173]. Unlike tetragonal chalcopyrite, talnakhite is characterized by a predominance of metal over sulphur and of Cu over Fe, and is the variety of chalcopyrite with the highest copper content. Its content of Ni attains 0.85 wt %, i.e. is greater than in any of the other minerals from this group except for abnormally anisotropic cubic chalcopyrite. Secondary alterations of talnakhite are in the form of its replacement by valleriite and late magnetite. p.78

Mooihoekite. Mooihoekite differs macroscopically from tetragonal chalcopyrite because of its colour which is similar to that of bornite, and it differs from talnakhite in that it lacks the bright variegated tarnish of the latter on the surface of its samples. Under the microscope, at crossed nicols, it is distinctly anisotropic. A characteristic feature of mooihoekite is the fine polysynthetic twinning of its crystals (Plate VII,b). Mooihoekite associates with the same minerals as talnakhite (Plate VII,c), but, unlike the latter, contains no inclusions of tetragonal chalcopyrite as exsolution products. It differs very slightly from talnakhite and cubic chalcopyrite in the magnitude of reflectance (see fig. 19).

TABLE 19

Composition of chalcopyrite group minerals (weight %, X-ray micro-analysis)

Mineral	Analysis Number	Cu	Fe	Ni	S	Total	Formula
Tetragonal chalcopyrite	1	35.01	30.80	0.053	33.88	99.74	$Cu_{1.04}Fe_{1.04}Ni_{0.001}S_2$
	2	35.0	30.0	-	33.4	98.4	$Cu_{1.09}Fe_{1.06}S_2$
	3	35.74	30.33	0.82	32.14	99.03	$Cu_{1.12}Fe_{1.08}Ni_{0.08}S_2$
	4	33.50	30.80	0.23-0.96	33.71	98.25-98.98	$Cu_{1.00}Fe_{1.04}Ni_{0.03}S_2$
	5	33.16	32.91	0.26	33.68	100.01	$Cu_{0.99}Fe_{1.11}Ni_{0.01}S_2$
	6	31.39	34.05	0.2	35.09	100.73	$Cu_{0.90}Fe_{1.02}Ni_{0.01}S_2$
Talnakhite	7	36.8	29.8	0.7	34.0	101.3	$Cu_{18}(Fe, Ni)_{16}S_{32}$
	8*	$\frac{36.86\text{-}37.36}{37.15}$	$\frac{28.79\text{-}29.48}{29.10}$	$\frac{0.70\text{-}0.87}{0.75}$	$\frac{33.06\text{-}33.84}{33.31}$	$\frac{99.97\text{-}100.69}{100.31}$	$Cu_{18}(Fe, Ni)_{16}S_{32}$
Mooihoekite	9*	$\frac{35.3\text{-}36.2}{35.84}$	$\frac{31.4\text{-}31.9}{31.62}$	$\frac{0.3\text{-}0.5}{0.44}$	$\frac{32.1\text{-}32.9}{32.42}$	$\frac{99.1\text{-}101.5}{100.32}$	$Cu_{18}(Fe, Ni)_{18}S_{32}$
	10*	$\frac{34.87\text{-}36.71}{35.91}$	$\frac{31.38\text{-}32.40}{31.88}$	$\frac{0.24\text{-}0.30}{0.26}$	$\frac{31.93\text{-}33.29}{32.44}$	$\frac{99.51\text{-}100.94}{100.49}$	$Cu_{18}(Fe, Ni)_{18}S_{32}$
Cubic chalcopyrite	11	34.75	32.14	0.41	32.52	99.82	$Cu_{17}(Fe, Ni)_{17}S_{32}$
Abnormally anisotropic chalcopyrite	12	33.1	32.4	1.7	33.2	100.4	$Cu_{16}(Fe, Ni)_{19}S_{32}$
Haycockite	13*	$\frac{31.83\text{-}32.55}{32.16}$	$\frac{36.64\text{-}35.46}{35.03}$	$\frac{0.36\text{-}0.58}{0.40}$	$\frac{31.94\text{-}32.86}{32.41}$	$\frac{99.87\text{-}100.94}{100.14}$	$Cu_{16}(Fe, Ni)_{20}S_{32}$

FOOTNOTE. 1-Massive pyrrhotite ores; 2-Veinlet-impregnated pentlandite-chalcopyrite-pyrrhotite ores; 3 and 4-Talnakhite-cubanite ores, Oktyabr'skii deposit; 5 and 6-Troilite-mooihoekite-cubanite ores, Oktyabr'skii deposit; 7-Talnakhite ores; 8-Talnakhite [177] (average of five analyses); 9-Mooihoekite-cubanite ores, Oktyabr'skii deposit (average of seven analyses); 10-Mooihoekite [178]; 11 and 12-Mooihoekite-cubanite ores, Oktyabr'skii deposit; 8-10 and 13- The variation thresholds are shown in the numerator and the mean values in the denominator.

Microhardness II =259-269 kG/mm^2.

A characteristic feature of mooihoekite is that its X-ray diffraction patterns display, similarly to those of talnakhite, several lines in the region of low angles (d_a=7.48; 4.78; 4.36; 3.76Å). Furthermore, they clearly exhibit a "reversed" (relative to tetragonal chalcopyrite) intensity of lines of the tetragonal doublets (1.882-1.871 and 1.610-1.597Å), i.e. a brighter line of mooihoekite in place of a weaker chalcopyrite line. Parameters of the tetragonal unit cell a=10.58 and c=5.36Å.

With regard to its chemical composition mooihoekite is characterized, similarly to talnakhite, by a predominance of metals over sulphur and a constant Cu:Fe $\approx$ 1 ratio. Its content of nickel is almost half that recorded for talnakhite.

Cubic chalcopyrite is the most difficult mineral for identification both macroscopically and under the microscope. With regard to the shape of its crystals, magnitude of reflectance, degree of oxidability in the air, colour and structure of its aggregates in reflected light, cubic chalcopyrite is indistinguishable from mooihoekite. Only the very weak anisotropy of cubic chalcopyrite permits us to differentiate at crossed nicols between it and distinctly anisotropic mooihoekite or tetragonal chalcopyrite. Microhardness varying from 257 to 269kG/mm^2. Debyeograms of this phase are very clear and simple. At a close examination all the films reveal a faint line with d_a=3.74Å. The structure of this mineral is not yet clear. Cubic chalcopyrite can be readily distinguished from talnakhite by the absence from its X-ray diffraction patterns of lines with d_a=7.50Å. In addition to the predominance of metals over sulphur that is common for all the minerals of this group, cubic chalcopyrite is characterized by an unstable Cu:Fe ratio (with variation thresholds of 1.0 to 0.94). With regard to its nickel content it is close to mooihoekite.

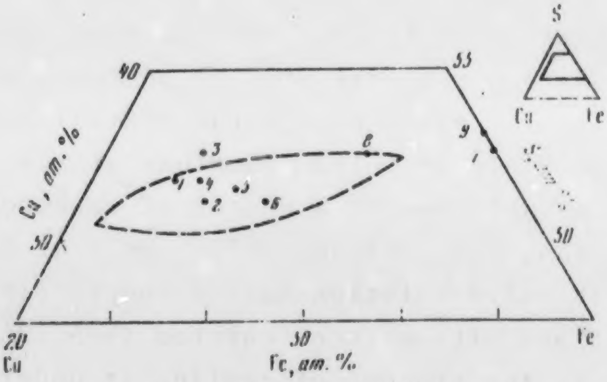
Abnormally anisotropic cubic chalcopyrite was initially discovered in mooihoekite and talnakhite ores [150]. Macroscopically this mineral is indistinguishable from talnakhite, since it also becomes rapidly oxidized in the air and acquires a bright tarnish. In reflected light it is close to mooihoekite and cubic chalcopyrite with respect to its reflection and colour, but differs sharply from all the minerals of that group because of its unusually strong anisotropy with bright greenish-grey to greyish-pink pleochroic effects. Barely perceptible bireflectance in freshly polished microsections. Anisotropy and bireflectance increase in intensity in polished microsections oxidized in the air. These phenomena may occur on account of the surface films. Because of the bireflectance and anisotropy of this mineral, the shape of its crystals and the structure of its aggregates are readily observable. It forms lenticular, lanceolate crystals measuring hundredths fractions of a millimetre to 1-2mm, tabular crystals or laths 0.1-0.5mm in width forming intricate lattice intergrowths with mooihoekite, cubic chalcopyrite and talnakhite p.79 (Plate VII,d). Only some of the tabular crystals are (judging from their simultaneous extinction) monomineral grains. Most of the crystals have an allotriomorphic-granular texture similar to the recrystallization texture of talnakhite. Microhardness varying within the limits of 252-266kG/mm^2. The debyeogram of this mineral is identical to that of the "cubic Pc-phase". Since its marked anisotropy is related in all probability to surface phenomena, we regard this chalcopyrite as another cubic phase with the edge of the unit cell equal to 5.30Å. This mineral has an increased content of iron (Table 19) and the highest nickel concentration (1.7 wt %). It differs from haycockite in both composition and properties.

The data presented above on the composition and intergrowths of chalcopyrite group minerals in the Noril'sk ores agree with the results of numerous experimental studies on the phase composition in the Cu-Fe-S system. The existence in the central part of that system of a large field of solid solutions at temperatures above 600°C has been established by a number of researchers [244, 269, 226, 200, 265, 290, 174 and 107]. Only at high temperatures does this solid solution have a completely disordered sphalerite-like structure with a face-centered (a=5.29Å) unit cell [200 and 174]. In the process of cooling it undergoes a series of extremely complicated alterations resulting in formation of transitional phases with a partly ordered arrangement of metal atoms ,to the fully ordered chalcopyrite (γ and β -phases, Pc-phase etc.) [226 and 174]. The number of the intermediate phases depends to a considerable degree on the Cu:Fe and Me:S ratios in the primary solid solution and on the conditions under which it cools.

With the exception of tetragonal chalcopyrite, all the minerals of the chalcopyrite group observed in the ores from the Noril'sk deposits, are located in the ternary diagram Cu-Fe-S in the field of the intermediate solid solution (fig. 20). In all of them metal predominates over sulphur; talnakhite has the highest content of copper; in mooihoekite and cubic chalcopyrite the ratio is Cu:Fe=1:1; and abnormally anisotropic cubic chalcopyrite belongs to the region of iron-rich solid solutions. The intergrowths of these minerals are similar to the experimentally obtained structures/as a result/of exsolution and alteration of solid phases in the process of cooling.

The absence from the Noril'sk ores of chalcopyrite with a face-centered cubic structure agrees with the experimental data obtained by L. Cabri [174] regarding the metastable nature of that phase. Its stability relative to high-temperature chalcopyrites with a Pc-structure, alongside mooihoekite and talnakhite, may p.80 be due to a sulphur deficiency at the moment of formation of these chalcopyrites, which also agrees with experimental data [237].

Fig. 20



Central part of the Cu-Fe-S system [174]; the region of the chalcopyrite solid solution is indicated with the dotted line.

1-Talnakhite; 2-Mooihoekite; 3-Tetragonal chalcopyrite; 4-Cubic chalcopyrite; 5-Abnormally anisotropic cubic chalcopyrite; 6-Haycockite; 7-Troilite; 8-Cubanite; 9-Hexagonal pyrrhotite.

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Cubanite

Cubanite, the second most important copper and iron sulphide of the Noril'sk ores after chalcopyrite, is extensively developed in massive and impregnated ores amidst intrusive rocks. It predominates, however, only in some of the massive ore types.

Cubanite is differentiated by the shape of its crystals into two most wide-spread varieties.

Platy or tabular crystals (0.01-0.2mm in width) of cubanite I are usually oriented in a regular manner in the grains of tetragonal chalcopyrite, talnakhite and mooihoekite; the orientation of platy cubanite I crystals varies in different grains of these minerals. In places there have been observed series of parallel platy crystals, which may cross at an angle of 60° forming a lattice texture (Plate VIII,a). This cubanite is probably a product of unmixing of the chalcopyrite solid solution.

Granular aggregates of cubanite II have grains measuring 0.1 to 5-7mm. They compose cubanite ores proper and form irregular agglomerations, veinlets or fringes around pentlandite and magnetite crystals in transitional chalcopyrite-cubanite, troilite-pyrrhotite-cubanite and talnakhite (mooihoekite)-cubanite varieties of ores (Plate VIII,b).

Fine-grained (0.1mm) cubanite has been observed considerably less often. It occurs here and there in the periphery of large cubanite grains or in the form of slender veinlets in the grains of other sulphides. Furthermore, cubanite has been encountered in carbonate veinlets in the form of small (0.1mm or less in diameter) tabular or platy crystals. All these varieties of cubanite have a rhombic modification.

The ores impregnated in intrusive gabbro-dolerites contain both platy and granular cubanites. The most abundant variety is cubanite I occurring in association with tetragonal chalcopyrite and iron-rich hexagonal pyrrhotite, as well as with troilite, talnakhite, mooihoekite and cubic chalcopyrite. Cubanite II, alongside with cubanite I and tetragonal chalcopyrite, occurs only in the ores, where chalcopyrite predominates over pyrrhotite. The variety predominating in associations with troilite, mooihoekite, talnakhite and cubic chalcopyrite, is cubanite II. The greatest abundance of cubanite has been recorded in massive ores, where it composes cubanite ores as such and a series of transitional mineral varieties of ores.

In massive cubanite ores it forms inequigranular aggregates with grains measuring 0.5 to 5-7mm. Amidst these aggregates there may be observed irregular masses of troilite (or pyrrhotite intergrown with troilite), talnakhite and other minerals of the chalcopyrite group, as well as pentlandite. The latter is represented in cubanite by spherical porphyritic phenocrysts and by grains varying in size and shape (0.01 to 0.1-0.2mm in diameter).

Massive aggregates of cubanite constantly change to systems of veinlets of a variable thickness, which cut across chalcopyrite-pyrrhotite, talnakhite and mooihoekite aggregates. Platy cubanite crystals are embayed, as a rule, in the grains of chalcopyrite and other minerals of that group. All these minerals become replaced by granular cubanite.

In veinlet-impregnated exocontact ores cubanite may occur in the form of platy inclusions in chalcopyrite from the pentlandite-cubanite-chalcopyrite varieties of ores.

Contrary to what has been observed in massive ores, in breccioid ores cubanite is a rare mineral and has been identified only amidst pyrrhotite-chalcopyrite ores, where it occurs in the form of platy crystals in chalcopyrite.

The types of cubanite agglomerations and crystals observed p.81 testify that it formed in two ways: as a result of unmixing of the chalcopyrite solid solution and by replacing earlier sulphides, i.e. pyrrhotite, pentlandite and minerals of the chalcopyrite group.

Analysis of the composition of cubanite from the main varieties of massive ores (Table 20) revealed no significant differences in the contents of its principal components, i.e. copper, iron, and sulphur. The compositions of its two main generations (platy and granular) and of the cubanites which form by replacing minerals of the pyrrhotite (hexagonal pyrrhotite and troilite) and chalcopyrite (chalcopyrite, talnakhite and mooihoekite) groups, proved to be very close. Nickel found in negligibly small concentrations in a few cubanites, is their only trace element.

TABLE 20

Composition of cubanite (wt %, X-ray micro-analysis)

Mineral varieties of ores	Sample Number	Cu	Fe	Ni	S	Total
Troilite-pyrrhotite	2406	23.20	40.60		36.00	100.40
Troilite-pyrrhotite-chalcopyrite	16047	23.00	40.10	0.01	36.00	99.80
Troilite-cubanite	2416	22.80	40.70		36.30	99.80
Chalcopyrite-cubanite	1674	22.80	40.30		36.80	99.90
	1248	24.00	39.00	0.01	36.20	99.20
Cubanite-talnakhite	2089	22.80	40.50		35.42	98.72
Mooihoekite-cubanite	2112	23.40	40.70		35.60	99.70
Cubanite-mooihoekite	1561	23.90	40.60		36.20	99.70

Magnetite

Magnetite is the only compound oxide with the structure of inverted spinel. It is widely distributed in all the types of the Noril'sk copper-nickel ores. Magnetite has been studied much less thoroughly than the essential ore-forming sulphides of the copper-nickel sulphide deposits. Experimental studies of the Fe-S-O system [248] are of great interest for clarifying the position of magnetite in the ores.

Occurrence and associations. In the ores from Noril'sk magnetite is closely associated with sulphides and is represented by numerous generations differing in the time of formation and grain shape.

It forms small isometric grains in association with pyrrhotite, troilite and chalcopyrite. These grains may be intergrown with grains of ilmenite and occur amidst small interstitial agglomerations of these sulphides in the ores impregnated in intrusive gabbro-dolerites. Larger (up to 2-3mm) magnetite grains with characteristic platy exsolution products of ilmenite that are found in drop-like agglomerations of sulphides, and small magnetite grains found along the boundary between the upper chalcopyrite portion of the drop-like insets and picrite gabbro-dolerites, also occur in these ores.

Magnetite is represented by the greatest diversity of forms in its associations with pyrrhotite and chalcopyrite in massive ores. In massive large-grained ores magnetite is commonly represented by grains measuring up to 1-3mm that are often round or oval in outline (Plate VIII,c). There have also been observed regular or skeletal grains with bizarre outlines and small (0.05 to 0.1mm) idiomorphic crystals.

Minutest platy magnetite crystals (Plate VIII,d) regularly disposed along the basal parting [17], are often found in pyrrhotite.

Magnetite grains are unevenly distributed amidst the sulphides and often form concentrations in pyrrhotite along its boundary with chalcopyrite or, less often, in chalcopyrite itself. Continuous fringes of large magnetite grains (up to 1cm) and abundant magnetite insets at the contacts of sulphide veins and deposits are highly characteristic formations. In the fringes magnetite may be closely associated with fluorine-apatite [21].

Magnetite is most abundantly developed in small-grained massive ores with silicate inclusions. Small (0.02-0.2cm) grains of magnetite occur amidst the sulphides, on the boundary p.82

of sulphide aggregates with silicate inclusions, and are densely disseminated within the inclusions. Titanomagnetite with lattice textures resulting from exsolution of platy ilmenite crystals, occurs in these ores alongside magnetite.

Small grains disposed predominantly along the boundary of the sulphides with silicate minerals of the country rock, but also within the sulphides, are the characteristic form in which magnetite occurs together with pyrrhotite and chalcopyrite in veinlet-impregnated and breccioid exocontact ores.

Magnetite is also constantly found in association with cubanite and minerals of the chalcopyrite group. In the ores composed of these minerals it forms large spherical grains and regular, sometimes skeletal, crystals. There have also been observed fringes and agglomerations of magnetite grains in the hanging wall of the ore bodies, to which increased contents of platinum minerals are confined [20].

Of great interest are instances, where magnetite occurs in "miarolitic" cavities in chalcopyrite and talnakhite ores. These cavities varying in size from 1 to 10mm, may be lined with well-formed octahedral magnetite crystals. Magnetite is found inside the cavities in intergrowths with columnar pyrrhotite crystals represented by hexagonal prisms, whereas in the cavities in talnakhite it occurs together with small platy crystals of valleriite.

Later generations of magnetite that evolved during the hydrothermal stage of ore formation, are abundantly represented in all the types of ores. Magnetite forms discrete veinlets cutting across the early sulphides, or, in association with other late minerals, replaces aggregates of these sulphides. Its most typical associations are those with pyrite, nickeloan pyrite, marcasite and valleriite. In magnetite-pyrite intergrowths magnetite forms thin lenticular parallel veinlets disposed along the basal parting of the former pyrrhotite grains (Plate IX,a). In this association it also occurs in the form of larger grains alternating with the loci composed of pyrite. There have also been observed intergrowths of late magnetite with valeriite, when the minerals replaced is chalcopyrite, or with tochilinite in the event of its replacing pyrrhotite.

Composition. The magnetites associated with sulphides in different types of ores have characteristic features of composition determined by the contents and ratios of their trace elements, such as chromium, titanium, magnesium, aluminum or vanadium.

Magnetites of the ores impregnated in intrusive gabbro-dolerites have increased contents of titanium and chromium (Table 21). The highest titanium concentrations have been recorded in the magnetites found in association with ilmenite, pyrrhotite and chalcopyrite and forming small crystals in interstices of the rock-forming silicates. These magnetites also have the highest nickel contents (up to 0.45%).

TABLE 21

Composition of magnetite from the ore impregnated in picrite gabbro-dolerite (wt %, X-ray micro-analysis)

Numbers of the analyses	V_2O_5	TiO_2	Al_2O_3	Cr_2O_3	Fe_2O_3*	FeO*	MnO	MgO	NiO	Total
1	0.70	7.50	-	9.10	43.40	35.60	0.50	0.90	0.40	98.10
2	0.46	8.70	-	3.24	47.60	36.10	0.47	1.30	0.45	98.32
3	-	2.80	1.50	8.50	52.20	31.50	-	1.16	0.18	97.84
4	-	2.10	0.70	0.57	62.20	31.10	-	0.87	0.17	98.11

1 and 2-magnetites associated with interstitial sulphides and ilmenite; 3 and 4-magnetites disposed above the drop-like insets of sulphides; *FeO and Fe_2O_3 have been obtained in the analyses by calculation.

The most indicative variations for magnetites from massive pyrrhotite ores are those of their titanium and vanadium contents. The highest concentrations of these elements have been recorded in pyrrhotite veins from the Noril'sk deposit in the flanges and grains of magnetite disposed along the upper and lower contacts of the veins. In a vein measuring 1m in thickness the content of titanium in the magnetite from the lower contact is up to 8% and that of vanadium is 1.3% (Table 22). It is particularly interesting that 10mm from the upper and 2cm from the lower contact, as well as in the centre of the vein, magnetite grains contain no titanium or vanadium. An analogous relationship has been established in the magnetite from a pyrrhotite vein occurring in labrador porphyrites, where its grains from the contact-line flange contain 2.08% Ti and 0.14% V, whereas even 5mm away from the flange the concentrations of these elements drop to 0.36% and 0.06, respectively. A complete chemical analysis of magnetite from that flange yielded the following data (in wt %): SiO_2 - 0.20, TiO_2 - 3.91, Al_2O_3 - 1.15, Fe_2O_3 - 60.31, FeO - 32.86, MnO - 0.40, MgO - 0.70, V_2O_5 - 0.23, NiO - 0.19, CoO - 0.02, and S - 0.07; total - 100.04. p.83

TABLE 22

Titanium and vanadium contents in magnetites from a pyrrhotite vein occurring in picrite gabbro-dolerites

Numbers of polished microsections	Location of magnetite grains	Ti,wt %	V, wt %
184	From the flange along the upper contact of the vein	2.60	0.70
		2.80	0.79
		3.08	0.80
	A spherical grain 7mm away from the flange	-	-
185	A spherical grain from the centre of the vein	-	-
	A lamella in pyrrhotite from the centre of the vein	-	-
183	2cm from the lower contact of the vein	-	-
	5-7mm from the lower contact of the vein	2.72	0.81
	Magnetite grains along the lower contact of the vein	7.07	1.14

FOOTNOTE. Here and in subsequent tables the dash indicates that the content recorded is nil within the detection limits of the technique employed.

These figures show a fairly good coincidence with the data presented earlier on the Ti and V contents on the basis of a microprobe analysis.

Even more complex patterns of titanium and vanadium distribution in magnetites have been established in the section of thicker pyrrhotite ore deposits at the Talnakh ore field (Table 23). In these deposits there have been recorded increased titanium and vanadium concentrations in magnetites from small-grained ores with silicate inclusions, whereas in magnetites from massive large-grained ores with a knitted arrangement of chalcopyrite around the pyrrhotite grains, the contents of these elements are considerably lower or nil. Moreover, the content of titanium in magnetite from ores of the same type is not a function of the shape or size of their grains or of the composition of the minerals in which they occur.

The magnetites associated with pyrrhotite in breccioid ores (Table 24) differ from the magnetites examined above in having higher contents of magnesium (up to 4.8%), aluminum (up to 3.40%) and manganese (up to 1.23%). It is characteristic that in the magnetites from the loci of massive ores occurring amidst breccioid ore varieties, these elements and titanium are either lacking or occur in negligibly small quantities.

The grains of magnetite associated in massive ores with cubanite, chalcopyrite, talnakhite and mooihoekite, contain as a rule only manganese (0.3-0.7%) and nickel (0.07-0.14%).

In the magnetites of later generations found in association with pyrite, nickeloan pyrite and millerite that formed as a result of the replacement of pyrrhotite and pentlandite, titanium and vanadium are found in minor quantities or lacking (Table 25). The highest concentrations of manganese p.84
- 1.76% (magnetite+pyrite association) and nickel - 0.47% (magnetite+nickeliferous pyrite+millerite association) have been recorded in these magnetites.

TABLE 23

Distribution of titanium and vanadium in different morphological varieties of magnetite in the section of pyrrhotite ore deposit

Sample Number	Type of ore	Shape and intergrowth of magnetite grains	Wt %, X-ray micro-analysis Ti	V
14108	Small-grained with inclusions of silicates	Large grain with inclusion of silicates in Po	0.90	0.07
			0.81	0.05
		Small grain with a silicate border in Cp	0.83	0.05
		Large spherical grain in Po	0.85	0.07
14109	Large-grained knitted	Spherical grain in Po	-	-
		Spherical grain in Pn	-	-
		Small grain at the Po-Pn boundary	0.01	0.01
14111	Small-grained with inclusions of silicates	Small grain in Po	1.06	0.28
			0.91	0.26
		Large spherical grain in Po	1.04	0.31
		Spherical grain in silicates	0.83	0.28
14113	Large-grained knitted	Xenomorphic grain in Po	-	-
		Small grain in Po	-	-
14115	Large-grained knitted	Grain with inclusions of silicates in Cp	0.01	0.03
			-	-
		Elongated grain in Po	-	-
		Grain in Po	-	-
		Spherical grain in silicate	1.96	0.15
14118	Small-grained with inclusions of silicates		1.93	0.14
		Spherical grain in Po	1.73	0.13
			1.83	0.12

TABLE 24

Composition of magnetites from breccioid ores (wt %, X-ray micro-analysis)

Sample Number	Fe_2O_3	Al_2O_3	MgO	TiO_2	MnO	NiO	V_2O_5	Total
1587	90.84	2.26	4.87	0.56	0.87	0.06	-	99.46
2597	90.83	3.40	2.25	0.60	1.23	0.15	0.07	98.53
6314	91.17	2.83	2.60	1.45	0.94	0.12	0.10	99.21
13700*	98.57	-	-	0.13	0.59	0.06	0.07	99.42

* A locus of massive ores

TABLE 25

Composition of magnetite from associations with pyrite and nickeloan pyrite (wt %, X-ray micro-analysis)

Sample Number	Fe_2O_3	MgO	TiO_2	MnO	NiO	Total
7637	96.99	0.54	0.03	1.76	0.03	99.35
11092	97.54	0.08	0.03	0.09	0.47	98.21

Alterations. Magnetite from different associations with sulphides may undergo alterations under the effect of solutions during the hydrothermal stage of ore formation. p.85

Magnetites from intergrowths with silicate minerals in impregnated or exocontact ores and those from massive ores with silicate inclusions become replaced by hydrous silicates (of the chlorite and serpentine group) finely dispersed in magnetite grains. Lamellas of ilmenite that have been observed in some of the magnetites remain, however, intact and persist in the form of a lattice framework in the magnetite that has been completely replaced. Another typical alteration of magnetite is its replacement by valleriite. In talnakhite, mooihoekite and cubanite there may be encountered complete pseudomorphs of valleriite in magnetite. Partial or complete pseudomorphs composed of a complex combination of minerals represented by pyrophanite, rutile, valleriite, hydrous silicates and other minerals, form here and there in large grains of magnetite, in its borders at the contacts of pyrrhotite and pyrrhotite-chalcopyrite veins with picrite gabbro-dolerites.

ACCESSORY ORE MINERALS

Pyrite, nickel- and cobalt-containing pyrite

Pyrite occurs in small quantities in all the types of ores, but is most abundantly represented in veinlet-impregnated exocontact ores, where in some loci it is the predominant sulphide. The Noril'sk ores, in addition to common pyrite, invariably contain its varieties comprising nickel or cobalt that are particularly clearly observable in zoned crystals (Plate IX,b) and in aggregates due to their characteristic pink colour.

In impregnated ores from intrusive gabbro-dolerites idiomorphic crystals (measuring up to 5mm) and irregularly shaped aggregates of pyrite are commonly associated with monoclinic pyrrhotite. In massive pyrrhotite ores it occurs predominantly in the locales of ore deposits situated near faults or disturbances.

In pyrrhotite mineral varieties of all the ore types pyrite develops as a mineral replacing pyrrhotite and forms in it metacrystals (Plate IX,b) or aggregates of fine intergrowths with magnetite and marcasite. Complete replacement of pyrrhotite in veinlet-impregnated ores leads to the formation of magnetite-pyrite or valleriite-pyrite ores, where large zoned metacrystals of pyrite occur amidst the fine intergrowths of these minerals. Pyrite also develops in chalcopyrite exocontact ores. Distinctive structures arise when it selectively replaces platy crystals of pyrrhotite (Plate IX,c) in pyrrhotite-chalcopyrite breccioid ores. The most complex intergrowths of pyrite with millerite and polydymite or violarite form as a result of exsolution of pentlandite.

The Noril'sk pyrites invariably contain nickel and cobalt, but the largest quantities of these elements have been recorded in isolated zones of zonal pyrite crystals (Table 26). The ratios, the disposition of the zones in relation to one another, and the contents of nickel and cobalt in them may vary. In some cases the highest nickel and cobalt concentrations are confined to the same zone; in others the zone with the highest nickel content is located in the centre of the zoned crystals and that with the largest quantity of nickel in its periphery (Plate IX,d and e). Maximum contents of nickel attaining 10.8% (Table 26) have been established in the nickeloan pyrite forming, together with polydymite, pseudomorphs in pentlandite.

At the present time there is no universally accepted nomenclature for minerals of the FeS_2 - NiS_2 - CoS_2 system. It has been suggested by I. Mincheva-Stefanova [113] that the minerals containing 80 to 100 mol.% of the essential component be referred to the end members, i.e. pyrite, vaesite and cattierite, and the minerals comprising all of the three components with contents of 10 mol. % or more be referred to bravoite (fig. 21). According to this classification the pyrites from samples 2985 and 68/41 with nickel contents of 10.8 and 9.9 wt % (Table 26) should be designated as nickelpyrites. p.87

The variations in the contents of nickel and cobalt in the pyrites examined above are due to the compositional differences of the primary minerals from which they evolved. High contents of nickel and cobalt arise as a result of the replacement of pyrrhotite containing small inclusions of pentlandite. Lower concentrations of these elements arise when pyrite evolves from pyrrhotite of pyrrhotite-chalcopyrite ores containing no pentlandite inclusions; the highest nickel contents are believed to form in the pyrite evolving as a result of exsolution of pentlandite. The compositions of pyrite and nickeloan pyrite thus testify to the importance of the chemistry inherited from primary minerals.

TABLE 26

Composition of pyrite and of nickel- and cobalt-containing pyrites (wt %, X-ray micro-analysis)

Ores, mineral varieties	Sample number	Fe	Ni	Co	Cu	S	Total	Formula
Massive pyrrhotite	12/40, zone with Ni_{max}	40.8	5.2	0.1		53.3	99.4	$(Fe_{0.878}Ni_{0.107}Co_{0.002})_{0.987}S_2$
	12/40, zone with Co_{max}	37.0	0.3	9.1		53.2	99.6	$(Fe_{0.798}Co_{0.186}Ni_{0.006})_{0.99}S_2$
	12/40, zone with Fe_{max}	46.5	0.1	-		53.6	100.2	$(Fe_{0.995}Ni_{0.002})_{0.997}S_2$
Veinlet-impregnated ores; pyrite-chalcopyrite	651, zone 1	47.0	0.08	0.05	0.27	53.0	100.4	$(Fe_{1.02}Cu_{0.01})_{1.03}S_2$
	651, zone 2	44.5	2.9	0.13	0.35	52.2	100.08	$(Fe_{0.92}Ni_{0.06}Co_{0.01}Cu_{0.01})_{0.99}S_2$
	651, zone 3	46.5	1.1	0.04	0.43	52.2	100.27	$(Fe_{1.02}Ni_{0.02}Cu_{0.01})_{1.04}S_2$
	11092							
	Central zone (1)	n.d.*	1.2	1.4	n.d.*	n.d.*		
	Intermediate zone (2)	n.d.*	4.7	0.2	n.d.*	n.d.*		
	Marginal zone (3)	n.d.*	2.5	0.8	n.d.*	n.d.*		
Millerite-chalcopyrite	2985	36.5	10.8	0.2	0.08	52.8	100.38	$(Fe_{0.80}Ni_{0.22}Co_{0.01})_{1.02}S_2$
	68/41, Central zone	46.2	-	-		53.6	99.8	$Fe_{0.989}S_2$
	68/41, Intermediate zone	37.2	9.9	-		53.3	100.4	$(Fe_{0.801}Ni_{0.203})_{1.004}S_4$
	68/41, Marginal zone	44.9	1.4	-		53.6	99.9	$(Fe_{0.962}Ni_{0.029})_{0.991}S_2$

* n.d. = not determined. Translator.

Marcasite

Marcasite occurs in the same types of ores as pyrite, with which it is usually intergrown, but in considerably smaller quantities than the latter. It forms small agglomerations amidst aggregates of pyrite or pyrite and magnetite.

In addition to its essential components, marcasite contains nickel and cobalt: Fe - 45.0 wt %, Ni - 1.0, Co - 0.1 and S - 53.5.

Mackinawite.

A tetragonal sulphide of iron close in composition to troilite; described originally from the ores of the Noril'sk deposits by A.D. Genkin and N.L. Vyal'sov [29]. It occurs in impregnated ores amidst intrusive rocks, as well as in deposits of massive ores, in a close association with pentlandite, chalcopyrite, cubanite, pyrrhotite and troilite. In both types of ores mackinawite is confined predominantly to their copper-bearing varieties.

In massive pentlandite-chalcopyrite, pentlandite-talnakhite or mooihoekite ores mackinawite commonly develops in pentlandite. In porphyritic phenocrysts of pentlandite the meshwork of minutest mackinawite veinlets gradually grows denser and changes to massive aggregates. Thin mackinawite veinlets are found in chalcopyrite. In some places mackinawite, together with valleriite, replaces cubanite lamellas embayed in chalcopyrite. In talnakhite and mooihoekite ores, where mackinawite replaces porphyritic phenocrysts of pentlandite, it may be associated with copper-containing pentlandite. In pyrrhotite-troilite-chalcopyrite or pyrrhotite-troilite-talnakhite ores mackinawite veinlets have also been observed in pyrrhotite and troilite.

In impregnated ores mackinawite also replaces predominantly pentlandite and forms slender veinlets in chalcopyrite and pyrrhotite. Here and there mackinawite surrounds thin lamellas of magnetite embayed in pyrrhotite. In picrite gabbro-dolerites mackinawite has been observed together with late pyrrhotite in the olivine grains replaced by bowlingite.

The fact that mackinawite replaces early sulphides (pentlandite, chalcopyrite etc.) and its constant association with valleriite and late magnetite suggest that this mineral may have formed as a result of hydrothermal reactions with earlier minerals.

Fig. 21

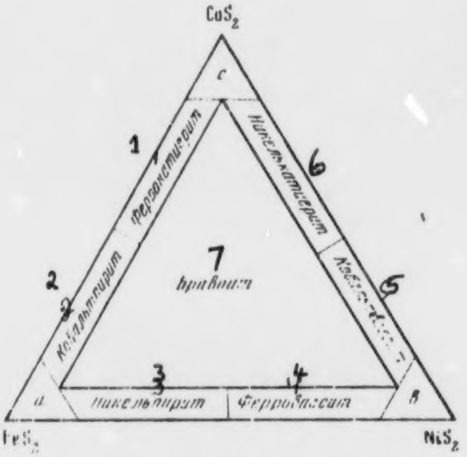

Diagram to the nomenclature of the minerals from the FeS_2-NiS_2-CoS_2 series after [113].
1-Ferrocattierite; 2-Cobaltpyrite; 3-Nickelpyrite; 4-Ferrovaesite; 5-Cobaltvaesite; 6-Nickelcattierite; 7-Bravoite.

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Optical properties. Mineral anisotropic, uniaxial, positive. Bireflectance very strong. In reflected light colour varying from p.88 creamy yellow to grey. Reflectance (R_g and R_p,%): 440nm - 35.9 and 21; 460 - 38.1 and 21; 480 - 40.2 and 21; 500 - 42.0 and 21.9; 520 - 43.2 and 21.3; 540 - 44.1 and 21.5; 560 - 44.9 and 21.7; 580 - 45.7 and 21.9; 600 - 46.3 and 22.2; 620 - 46.9 and 22.7; 640 - 47.3 and 23; 660 - 47.6 and 23.3; 680 - 47.8 and 23.7; 700 - 48.0 and 22.0; 720 - 48.2 and 22.3; and 740 - 48.4 and 22.6.

The chemical compositions determined with the help of an X-ray micro-analyser (Table 27) show that mackinawites from different types of ores are represented by their nickeloan varieties. Their content of nickel does not, however, exceed 6.6 wt %; that of cobalt varies from 0.08 to 0.36 wt.%; and Me/S is roughly 1.

TABLE 27

Composition of mackinawite (wt %, X-ray micro-analysis)

Type of ore	Fe	Cu	Ni	Co	S	Total	Me/S
Troilite-pyrrhotite-chalcopyrite	55.7	0.5	6.6	0.11	36.0	98.9	0.99
Same as above	57.86	0.96	4.93	0.32	34.37	98.44	1.06
	59.53	0.39	4.84	0.36	33.26	98.38	1.11
Chalcopyrite	59.48	0.52	5.98	0.33	34.99	101.3	1.08
	59.86	0.63	5.86	0.17	35.00	101.52	1.08
Impregnated chalcopyrite-pyrrhotite ore in gabbro-dolerite	58.54	0.41	6.47	0.08	37.32	102.82	1.00

X-ray data. The strongest lines of the debyeogram: 5.04(10); 2.97(10); 2.32(9); 1.845(6); 1.810(8); 1.731(4); 1.571(3); 1.303(3); 1.135(3); and 1.054(5).

Millerite

Millerite, a mineral of nickel, is second in abundance after pentlandite. It occurs mainly in exocontact veinlet-impregnated and breccioid ores, where it is one of the principal ore-forming sulphides. Small quantities of millerite may also be found in massive and impregnated types of ores.

There have been distinguished two main generations of millerite belonging to asynchronous associations. Millerite of the earlier association is represented by large allotriomorphic-granular palmate or, occasionally, veinlet-like aggregates of grains and is associated with bornite and chalcopyrite, sometimes with chalcocite, heazlewoodite and godlevskite. It occurs in exocontact veinlet-impregnated and breccioid ores, as well as in thin veinlets composed essentially of copper, which diverge off the deposits of massive ores. Millerite of the later generation formed as a result of the exsolution of pentlandite in the process of the low-temperature hydrothermal autometamorphism of the ores. Concomitantly with millerite there evolved minerals, such as nickeloan pyrite, violarite, polydymite and in some cases vysotskite, forming regular intergrowths with millerite (Plate X,a). Crystals of the millerite from this association are commonly very small.

Under the microscope millerite displays an observable bireflectance with the colour varying from pale yellow to bluish-white, and at crossed nicols it is markedly anisotropic with pleochroic effect. This mineral has a characteristic dispersion of reflection (R_g and R_p,%): 440 nm - 35.5 and 38.3; 460 - 41.1 and 42.0; 480 - 45.7 and 44.3; 500 - 48.7 and 46.2; 520 - 50.9 and 47.7; 540 - 52.9 and 48.9; 560 - 58.3 and 49.8; 580 - 55.3 and 50.3; 600 - 55.7 and 51.0; 620 - 56.8 and 51.8; 640 - 57.7 and 52.8; 660 - 57.9 and 53.1; 680 - 58.3 and 52.8; 700 - 59.0 and 53.0; 720 - 59.1 and 53.4; and 740 - 59.4 and 53.7 with the optic sign changing* at 470 nm.

The composition of millerite (Table 28) is close to its theoretical composition. In addition to nickel and sulphur, there have been established in some samples minor quantities of cobalt, iron and copper. There are no substantial differences between the millerites of the early (samples 2822, 9251 and 23051) and later generations (samples 11092, 2958, etc.). p.89

TABLE 28

Composition of millerite in different types of ores (wt %, X-ray micro-analysis)

Sample Number	Ni	Co	Fe	Cu	S	Total	Formula
2822	62.78	-	0.9	0.5	35.5	99.68	$(Ni_{0.967}Fe_{0.015}Cu_{0.07})_{0.989}S$
9251	64.6	0.25	-	-	35.2	100.0	$(Ni_{1.005}Co_{0.005})_{1.01}S$
23051	64.2	0.4	-	-	35.3	99.9	$(Ni_{0.994}Co_{0.006})_{1.00}S$
11092	63.3	0.4	1.2	0.07	34.9	99.87	$(Ni_{0.830}Fe_{0.165}Co_{0.005})_{1.20}S$
2985	61.9	-	0.8	-	34.8	97.5	$(Ni_{0.970}Fe_{0.014})_{0.984}S$
9629a	63.1	1.1	0.6	-	35.6	100.4	$(Ni_{0.973}Co_{0.017}Fe_{0.010})_{1.00}S$
96296	64.2	0.1	0.4	-	35.2	99.9	$(Ni_{0.992}Fe_{0.006}Co_{0.002})_{1.00}S$
168/59	63.5	0.18	1.0	0.09	35.3	99.97	$(Ni_{0.983}Fe_{0.016}Cu_{0.001}Co_{0.001})_{1.00}S$

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* reversing. Translator.

FOOTNOTE. Samples 2822 and 9251 --- veinlet-impregnated bornite-millerite-chalcopyrite ores; 23051 --- a massive chalcopyrite ore veinlet; 11092 and 2985 --- veinlet-impregnated chalcopyrite-pyrite ore; 9629a and b, and 268/59--- veinlet-impregnated millerite-chalcopyrite ore.

The X-ray diffraction pattern of the millerite from Talnakh coincides with the standard X-ray diffraction pattern of millerite.

Polydymite

Polydymite is found rarely. It is most characteristic of millerite-chalcopyrite and millerite-bornite-chalcopyrite exocontact ores. Polydymite may develop together with millerite and nickeloan pyrite from pentlandite as a result of the unmixing of the latter under the effect of low-temperature hydrothermal solutions. Development of polydymite from millerite is also characteristic. There have occasionally been observed polydymite grains in the form of regular rectangular metacrystals amidst chalcopyrite and bornite (Plate X,b).

In reflected light polydymite is isotropic and has a lilac-greyish colour. Reflectance(R,%):440nm - 46.5; 460 - 46.8; 480 - 46.9; 500 - 46.9; 520 - 46.8; 540 - 46.7; 560 - 46.5; 580 - 46.7; 600 - 47.3; 620 - 48.1; 640 - 49.2; 660 - 50.0; 680 - 52.4; 700 - 54.1; 720 - 56.0; and 740 - 57.6. The reflection dispersion curve of the mineral resembles most closely that of siegenite.

The striking features in the composition of polydymite (Table 29) are the marked variations in its cobalt contents (0.9 to 15.3%) and the presence of iron. Polydymites with high cobalt concentrations occupy an intermediate position between polydymite and linnaeite and approach siegenite. They may be referred to as cobaltoan (Co^{2+}) polydymites.

TABLE 29

Chemical composition of polydymite (wt %, X-ray micro-analysis)

ample umber	Ci	Co	Fe	Cu	S	Total	Formula
1	53.9	9.9	3.0	0.01	42.0	99.8	$(Ni_{0.928}Fe_{0.055}Co_{0.015}Cu_{0.002})_{3.202}S_{4.00}$
2	44.2	13.6	0.9	-	40.6	99.3	$(Ni_{0.753}Co_{0.231}Fe_{0.016})_{3.16}S_{4.00}$
3	41.0	15.3	1.0	-	42.8	100.1	$(Ni_{0.715}Co_{0.266}Fe_{0.019})_{2.93}S_{4.00}$

FOOTNOTE. 1-Polydymite evolving together with millerite and nickeloan pyrite from pentlandite in pentlandite-chalcopyrite exocontact ores; 2 and 3-Polydymite from millerite-chalcopyrite ores.

Heazlewoodite

Heazlewoodite was discovered in the Noril'sk ores from the bornite-chalcocite veinlets branching off the chalcopyrite deposits into the taxite gabbro-dolerite country rock [103 and 81]. The composition of these veinlets varies from bornite near the deposit to bornite-chalcocite or chalcocite in the pinchout locales. Heazlewoodite is most widely distributed amidst chalcocite in the form of striking spherical agglomerations (0.5 to 4mm) or small irregularly shaped grains. Spherical agglomerations p.90 of heazlewoodite may also be observed amidst bornite with a profusion of small pentlandite inclusions. These heazlewoodite agglomerations found in bornite are fringed by chalcocite and may be intersected here and there by chalcocite veinlets. Heazlewoodite is also confined to the chalcocite veinlets cutting across pentlandite-bornite aggregates (Plate X,c). These correlations testify that we are dealing with two different generations of heazlewoodite: the earlier spherical agglomerations arising together with bornite, possibly in part at the expense of porphyritic phenocrysts of pentlandite, and the small grains forming together with chalcocite in the veinlets intersecting bornite.

Heazlewoodite occurs in association with bornite and chalcocite in the form of insets in gabbro-dolerites and sedimentary-metamorphic rocks along their contact with deposits of talnakhite ores.

In reflected light heazlewoodite is light-yellow, with a very weak bireflectance, anisotropic. Reflectance (R,%): 440 nm - 41.7; 460 - 45.6; 480 - 50.4; 500 - 52.8; 520 - 54.5; 540 - 55.8; 560 - 56.4; 580 - 56.9; 600 - 57.0; 620 - 58.1; 640 - 58.9; 660 - 58.8; 680 - 59.8; 700 - 61.3; 720 - 61.0; and 740 - 61.8.

Principal lines of the debyeogram: 4.10(6); 2.88(10); 1.841(10); 1.828(8); 1é668(9); and 1.090(5).

Bornite

Bornite has been observed in all the types of ores, but occurs in significant amounts only in isolated loci near the veins or deposits of massive chalcopyrite ores and in veinlet-impregnated exocontact ores.

Bornite and bornite-chalcopyrite veinlets, which may sporadically contain carbonate, have been recorded at the Noril'sk deposit near chalcopyrite veins. In some cases bornite is found in association with porphyritic phenocrysts of pentlandite, which it replaces, and in others with millerite. Delicate traceries of veinlet-like maucherite crystals or maucherite borders may be observed in the veinlets amidst bornite or along its boundary with carbonate inclusions. In chalcopyrite veinlets from the Talnakh deposit bornite and chalcocite replacing chalcopyrite, develop in the selvages of the veins in the following manner: a small zone of chalcocite is situated right next to the selvage and is followed by bornite-chalcocite intergrowths, in which chalcocite replaces bornite succeeded towards the centre of the veinlet by a small zone of massive bornite with relicts of chalcopyrite and a closely spaced meshwork of bornite veinlets in chalcopyrite. In the diverging bornite veinlets that change to chalcocite veinlets as they move away from the chalcopyrite ore bodies, bornite is associated with heazlewoodite, as well as with pentlandite.

Bornite associated with talnakhite, here and there with chalcocite and heazlewoodite, has been identified among the components of sulphide phenocrysts in gabbro-dolerites near the deposits of massive talnakhite (mooihoekite) ores.

In the ores impregnated and veinlet-impregnated in the sedimentary-metamorphic rocks of the exocontacts in gabbro-dolerite intrusions, bornite occurs in association with chalcopyrite or with millerite and chalcopyrite in the locales farthest from the intrusions. Its intergrowths with the minerals mentioned above form minutest crystals amidst rock-forming silicates, as well as agglomerations and veinlets.

In very rare instances bornite occurs together with chalcopyrite in the form of minutest crystals in the ores impregnated in picrite gabbro-dolerites.

The composition of bornite determined with the help of an electron-probe is close to the stoichiometric Cu_5FeS_4. In two grains of bornite from bornite-chalcopyrite veinlet-impregnated ores (wt %): Cu - 63.2 and 63.5; Fe - 11.7 and 11.6; and S - 26.1 and 26.0. The formulas are $Cu_{4.89}Fe_{1.03}S_{4.00}$ and $Cu_{4.92}Fe_{1.03}S_{4.00}$, respectively. Some bornites contain small amounts of nickel (fractions of a per cent).

Chalcocite

Chalcocite is found rarely in ores, but forms here and there discrete veinlets up to 20cm in thickness. The veinlets diverge off the Talnakh chalcopyrite deposit into the taxite gabbro-dolerite country rock. In the chalcopyrite veins of that deposit it occurs occasionally along the selvages where it replaces chalcopyrite. In these ores chalcocite is invariably associated with bornite, which it replaces, or, less often, is found in association with heazlewoodite. Chalcocite has been observed together with these minerals in the sulphides impregnated in gabbro-dolerites, and in the country rock near p.91

the deposits of massive talnakhite or mooihoekite ores. In bornite-chalcopyrite veinlet-impregnated ores chalcocite forms minutest (hundredth fractions of a millimetre) crystals in bornite.

In reflected light chalcocite is greyish-white with a bluish tint. Examination at crossed nicols reveals a weak anisotropy and a finely granular fabric of its aggregates.

The principal lines of the debyeogram of chalcocite 2.42(8), 1.985(9), 1.880(10), 1.693(3) and 1.285(3) correspond to the lines of the standard rhombic chalcocite.

Sphalerite

Small quantities of sphalerite are present in all the types of ores. There have been identified three generations of that mineral. The earliest sphalerite I occurs in the form of minutest single dendroid crystals in chalcopyrite, mooihoekite and talnakhite and is probably a product of unmixing of a zinc-containing chalcopyrite solid solution. Next in age is sphalerite II, which forms part of the association of platinum minerals [20]. It is represented by xenomorphic, sometimes elongated crystals resembling veinlets with undulate boundaries, and may be found in intergrowths with minerals of the platinum group, djerfisherite, shadlunite, altaite, galena and other rare minerals belonging to that association. The grains of sphalerite vary in size from a few tens to a couple of hundreds of μm. The occurrence of the most recent sphalerite III is related to the action of low-temperature hydrothermal solutions [57]. Sphalerite III associates with carbonates, pyrite, galena, arsenides, diarsenides and sulphoarsenides of nickel, cobalt and iron. Its grains form aggregates measuring up to a few centimetres.

Determinations of the composition of sphalerites II and III show that they contain nickel and cobalt in addition to iron, copper, manganese and cadmium that are common trace elements in that mineral (Table 30).

TABLE 30

Composition of sphalerite (weight %, X-ray micro-analysis)

Sample Number	Zn	Fe	Cu	Cd	Co	Ni	Mn	S	Total	Generation
21709	54.76	6.31	3.95	2.97	0.03	0.03	0.10	32.84	100.99	II
71	56.7	6.7	0.8	2.2	-	-	-	30.9	97.3	II
75	54.3	7.8	1.5	1.3	-	-	1.2	31.2	97.3	II
2047	50.6	9.9	-	3.0	-	-	4.2	31.2	98.9	II
26052	58.64	6.57	0.28	1.96	0.02	n.d.*	0.07	33.42	100.96	II
9251	61.77	0.73	0.60	5.82	0.01	0.01	0.01	31.61	100.53	II
21923	58.32	8.25	0.19	0.11	0.04	0.23	0.11	35.00	102.25	III
18044	56.78	9.53	0.12	0.41	0.06	0.01	0.07	34.48	101.47	III
23152	61.32	5.85	0.02	0.13	0.06	0.05	0.03	33.66	101.13	III

FOOTNOTE. Samples 21709, 21923 and 18044 - from the ores impregnated in intrusive rocks; samples 71,75,2047,26052 and 23152 - from massive ores; sample 9251 - from veinlet-impregnated exocontact ores; dashes indicate that the elements in question were not determined in the mineral.

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* not detected. Translator.

Sphalerites II and III differ markedly in their contents of the elements listed above. Sphalerite II is characterized by high cadmium, manganese and copper concentrations and by low contents of nickel and cobalt, whereas sphalerite III contains increased amounts of nickel and cobalt, but has low contents of copper, manganese and cadmium. The content of iron is roughly the same in the sphalerites of different generations, except for the sphalerite from bornite-millerite-chalcopyrite ores (sample 9251).

Under the microscope sphalerite is grey with a bluish p.92
tinge that is more intensive in sphalerites I and II. At crossed nicols it is isotropic. Because of its greater contents of cadmium, sphalerite II has higher reflectance values. For sphalerite III (0.13%Cd) and sphalerite II (9.2%Cd) reflectance

(R, %) is as follows: 440 mn - 16.2 and 20.4; 460 - 16.2 and 19.5; 480 - 16.0 and 18.7; 500 - 15.9 and 18.0; 520 - 15.7 and 17.5; 540 - 15.5 and 17.4; 560 - 15.4 and 17.2; 580 - 15.3 and 17.1; 600 - 15.2 and 17.1; 620 - 15.0 and 17.0; 640 - 14.8 and 17.0; 660 - 14.7 and 16.9; 680 - 14.5 and 16.8; 700 - 14.4 and 16.8; 720 - 14.2 and 16.9; 740 - 14.0 and 17.0%. Indentation harndess of these samples is 107-284 (average 183) and 247-308 (average 280) kg/mm^2.

Galena

Galena has been encountered in all the types and mineral varieties of ores, but its quantity is usually small. In characteristic paragenetic sequences there have been distinguished two main generations of this mineral: galena associated with minerals of noble metals and tellurides, and galena from relatively low-temperature carbonate veins and veinlets, where it is associated with sphalerite, arsenides, diarsenides and sulphoarsenides of nickel, cobalt and iron.

Agglomerations of the galena from the former association are commonly small. The mineral forms spherical or xeromorphic grains amidst the principal ore-forming sulphides and often encrusts crystals of platinum metals. In some, fairly rare, instances there have been encountered locales of massive, essentially cuproan ores which commonly gravitate towards the upper selvage of the deposit. Galena is one of the principal ore-forming sulphides in these ores. These galena-chalcopyrite (mooihoekite and bornite) grains are spherical in shape and vary in size. Within the crystals galena and chalcopyrite (mooihoekite and bornite) form subgraphic intergrowths resembling eutectic aggregates (Plate X,d). Large aggregates of grains of platinum minerals, as well as tellurides (hessite and altaite) may be confined to this kind of locales.

Galena-rich loci have also been recorded in veinlet-impregnated exocontact ores.

Of great interest are platy galena crystals oriented at an angle of 90° in relation to one another, that are found in bornite from the upper selvage of the mooihoekite ore deposit; they resemble products of exsolution.

Galena crystals also attain a large size (up to a few centimetres) in carbonate veins and veinlets. They are xenomorphic in form and are closely intergrown with sphalerite III and with calcite. These minerals intensively replace pyrrhotite and chalcopyrite of massive ores, but leave pentlandite intact and its lamellas persist in galena, as well as in sphalerite and calcite.

The galenas from the paragenetic sequences described above also differ in chemical composition (Table 31). Those of the first kind have increased (0.2-8.8%) contents of selenium and may be referred to the selenian variety of that mineral [85]. p.93
It has been established that the galena comprising altaite as a product of exsolution, contains up to 0.4% tellurium, while the galena from breccioid ores, in which fusiform crystals of "sulphosalts of silver, copper, lead and antimony" perpendicular to one another have been identified, contain increased concentrations of these elements (Table 31, sample 14381).

Optic properties of galena depend to a significant degree on its selenium content: as the concentration of that element increases, the mineral acquires a bluish tint in reflected light and the magnitude of its reflectance rises [86].

TABLE 31

Composition of galena from different types of ores (weight %, X-ray micro-analysis)

Sample Number	Pb	Ag	Cu	Ni	Sb	Te	Se	S	Total
19191	86.6	-	-	-	-	-	0.2	12.2	99.0
2823	85.0	-	-	-	-	-	0.55	13.1	98.65
2820	85.5	-	-	-	-	-	0.9	12.8	99.3
9155	82.1	-	1.9	0.7	-	-	1.2	13.6	99.5
19182	83.0	-	-	-	-	-	3.7	11.4	98.1
9037/1	80.9	-	-	-	-	-	8.8	9.2	98.8
14381	88.07	0.5	0.43	-	0.15	-	-	13.73	102.87
i-1973	86.50	-	-	-	-	0.80	-		100.3

FOOTNOTE. Samples 19182 and 19191---impregnated ores; i-1973---massive cubanite-chalcopyrite ores; 2820, 2823, 9037/1 and 9155---veinlet-impregnated exocontact ores; 14381---breccioid ores; dashes indicate that the elements in question were not determined.

Valleriite group minerals

Minerals of the valleriite group are widely distributed in massive and, particularly, veinlet-impregnated exocontact ores. In isolated parts of the ore bodies they are the essential or even the predominant minerals.

Attempts to decipher the complex composition and structure of these minerals succeeded only after detailed studies of their crystal structure and chemistry. H. Evans and R. Allmann [203] have demonstrated that valleriite has a mixed-layer structure and belongs to a special group of sulphides of hydroxide minerals. It is composed of alternating sulphide and brucite layers and has the formula $2[Cu,Fe]S.n\{[Mg,Fe,Al][OH]_2\}$. The structure of tochilinite, a new mineral of the valleriite group with the formula $2FeS\cdot 1.67\{[Mg,Fe,Al][OH]_2\}$, was established by N.I. Organova et al.[121]. Another nickel-containing mineral of the valleriite group that has been described is haapalaite [229] with the formula $Fe_{1.26}Ni_{0.74}S_2 \cdot 1.61\{[Mg,Fe][OH]_2\}$.

N.I. Organova et al. [122] summed up the information pertaining to the structural characteristics and isomorphous replacements of the valleriite group minerals.

In massive talnakhite, mooihoekite and chalcopyrite ores, valleriite forms veinlets in minerals of the chalcopyrite group and in cubanite, or replaces cubanite and magnetite forming here and there pseudomorphs in the spherical grains of the latter. Small platy crystals of valleriite intergrown with magnetite crystals of an octahedral habit, have been encountered in cavities of talnakhite ores. Valleriite has also been observed in pyrrhotite ores at the contact of their veins and deposits with picrite gabbro-dolerites or with the wall rock containing veinlet-impregnated ores.

The occurrence and associations of valleriite vary particularly widely in exocontact veinlet-impregnated and breccioid ores. In chalcopyrite varieties of these ores valleriite develops in the form of small-grained aggregates by replacing chalcopyrite, which persists occasionally only in the form of small relicts.

Larger grains of valleriite measuring tenth fractions of a millimetre have been observed in the cross veinlets of that mineral. In the ores, in a close association with valleriite, there has been recorded in some places magnetite and, which is particularly interesting, diaspore. Small irregularly shaped grains of the latter occur amidst the valleriite aggregates replacing chalcopyrite (Plate X,e). Valleriite is also found in essentially pyrrhotite ores, where it evolves in pyrrhotite. There have been observed different stages of replacement of pyrrhotite up until it vanishes completely and valleriite, valleriite-pyrite or valleriite-magnetite aggregates appear in its place. Flames and platy crystals of pentlandite in pyrrhotite may be unaffected by the replacement and persist in valleriite.

Depending on the occurrence of the valleriite group minerals in the ores, their composition varies with respect to a) the content of the "brucite molecule"; b) the composition of the hydroxide constituent; and c) the copper to iron ratio in the "sulphide molecule". A distinctive compositional characteristic of the valleriite from massive talnakhite ores is the absence of magnesium from it (Table 32). This valleriite differs from the Swedish valleriite variety because of its purely Fe-"brucite molecule". This kind of valleriite was originally discovered by Canadian researchers [219]. The valleriites found in veinlet-impregnated chalcopyrite ores, p.94 where magnesium-containing silicates are widely distributed amidst the rock-forming minerals, are similar in composition to the Swedish valleriite. However, valleriites with excessive contents of copper relative to iron in the sulphide fraction (Table 32), have also been frequently encountered in these ores. Valleriites of that composition have not been described in the literature. Veinlet-impregnated pyrrhotite ores contain valleriites with low copper contents and with iron predominating in their sulphide fraction (Table 32). These valleriites are close in composition to tochilinite.

TABLE 32

Composition of valleriite group minerals (weight %, X-ray microanalysis)

Type of ores	Cu	Fe	S	Mg	Al	Formula
Massive talnakhite ores	20.0	43.8	20.3	-	-	$Cu_{0.993}Fe_{1.005}S_2 \cdot 1.37[Fe(OH)_2]$
Veinlet-impregnated chalcopyrite ores	23.64	22.0	22.8	11.15	0.88	$Cu_{0.47}Fe_{0.953}S_2 \cdot 1.51(Mg,Fe)(OH)_2]$
Veinlet-impregnated pyrrhotite ores	9.0	35.5	23.3	10.4	0.52	$(Fe,Cu)S_2 \cdot 1.43[(Mg,Fe)(OH)_2]$
Deposit at Kaveltrop Sweden	18.6	29.5	23.3	11.5	-	$Cu_{0.93}Fe_{1.07}S \cdot 1.51(Mg,Fe)(OH)_2]$

The composition of the valleriites from the Noril'sk ores is thus controlled to a significant degree by the composition of the minerals amidst which they occur.

X-ray studies of valleriites show that they yield similar debyeograms close to that of the Swedish valleriite. The principal lines are as follows: 11.3 - 11.4(10); 5.62 - 5.70(10); 3.24 - 3.27(8); 2.84 - 2.87(6); 2.27 - 2.29(5); 1.894 - 1.903(8); and 1.867 - 1.870(7).

Only one sample of a copper-poor valleriite from pyrrhotite ores yielded a debyeogram characteristic of tochilinite with the lines 10.79(4); 5.40(10); 2.66(3) and 2.07(8). We succeeded in determining the structural characteristics of the Noril'sk valleriites much more completely with the help of the microdiffraction technique [122]. It has been established that the copper-poor valleriite is composed of finely intergrown valleriite and tochilinite. Its low content of copper relative to that of common valleriite can be explained not only by the presence of copper-free tochilinite, but also by the essentially ferroan composition of its sulphide component with the measured value of a sulphide below the norm.

Ilmenite

Ilmenite occurs in the ores considerably less often than magnetite. The ores impregnated in intrusive gabbro-dolerites are the only type of ores in which ilmenite is relatively abundant.

It is found in interstitial sulphides in intergrowths with titanium- and chromium-containing magnetite, but also forms discrete grains (up to 0.5mm in size) amidst the rock-forming silicates of gabbro-dolerites. In drop-like crystals of sulphides it may also be represented by larger (up to 2-3mm) grains. X-ray spectral micro-analyses of the composition of ilmenite from these generations show that, in addition to iron and titanium, it contains 2.5 to 5% MgO, 2 to 0.9%Cr_2O_3, 0.2-0.3% Al_2O_3 and up to 0.6% MnO. The characteristic features observed here are the presence of a chromium admixture that is relatively rare in ilmenites, and the fact that the intergrown ilmenite and magnetite have corresponding compositions with magnesium accumulating in the former, and chromium (up to 8-15%) and aluminum (up to 2%) in the latter. In impregnated and massive ores ilmenite forms platy crystals in magnetite (see magnetite).

Ilmenite aggregates with a distinctive flabellate internal structure have been observed in association with pyrrhotite and with magnetite that is represented by agglomerations of spherical grains in pyrrhotite ores. These aggregates occur in the centre of magnetite grains and are separated from magnetite by a thin border of hematite. These intergrowths may have formed in the process of unmixing of titanomagnetite grains. p.95

Hematite

Hematite is found rarely in the Noril'sk ores. Its occurrence is related mainly to the development of late generations of magnetite that form in association with pyrite and nickeloan pyrite by replacing pyrrhotite in exocontact or (less often) massive ores. In pyrite-magnetite intergrowths hematite replaces magnetite by forming borders (fringes) or small grains.

RARE MINERALS

Argentopentlandite

The find by K. Michener of silver-containing pentlandite in the Frood mine at Sudbury is mentioned for the first time in J. Hawley's work [222]. The mineral has been studied inadequately, but its unusual rusty-red colour and its intergrowths with platy pentlandite coincide with later and considerably more detailed descriptions of argentopentlandite [155, 287, 271 and 243].

Argentopentlandite has been encountered at the Noril'sk deposits in massive pyrrhotite, pyrrhotite-chalcopyrite and chalcopyrite-cubanite ores [155] and in breccioid pentlandite-chalcopyrite ores (Plate X,f). There have also been reported isolated finds of that mineral in the ores impregnated in gabbro-dolerites. Grains of argentopentlandite measuring up to 0.1-0.3mm in massive ores and up to 0.05mm in breccioid ore varieties, occur in chalcopyrite or at its boundary with pyrrhotite. Argentopentlandite replaces pentlandite, which may persist in it in the form of relict platy crystals or veinlet-like agglomerations.

Because of its pinkish-brown colour, argentopentlandite closely resembles bornite and may be easily mistaken for it. Isotropic. Reflectance higher than in bornite, but the shape of the reflection spectrum curve is close to that of bornite. Reflectance (R,%): 440nm - 24.5; 460 - 25.3; 480 - 26.2; 500 - 27.4; 520 - 28.5; 540 - 29.6; 560 - 30.8; 580 - 32.3; 600 - 33.4; 620 - 34.6; 640 - 35.9; 660 - 37.0; 680 - 38.3; 700 - 39.0; 720 - 39.9; and 740 - 40.7.

The characteristic compositional features of argentopentlandite (Table 33) are the constant presence of silver in it and its varying iron and nickel contents. It has been established that the compositions of the argentopentlandite and pentlandite found in association with one another, are interdependent: the pentlandite intergrown with a nickel-rich argentopentlandite also has a higher nickel content.

Studies on the structure of argentopentlandite [218] have demonstrated that it resembles the structure of pentlandite and that silver invariably occupies octahedral positions in that mineral. The size of the cubic primitive unit cell of argentopentlandite is a=1056Å. The principal lines of its X-ray diffraction pattern are 3.17(113); 3.035(222); 2.025(333); and 1.861(644).

Cuproan pentlandite

Discovered originally in the ores from the Talnakh deposit [114]. So far it has not been identified in deposits of any other region. Occurs in massive talnakhite-cubanite and mooihoekite-cubanite ores. Cuproan pentlandite is always confined to porphyritic phenocrysts of pentlandite, in which it evolves by replacing pentlandite. In these phenocrysts it forms here and there meshworks of slender veinlets changing to nearly complete pseudomorphs that may contain chalcopyrite and mackinawite. It has been observed that cuproan pentlandite contains relict platy crystals or meshworks of veinlet-like relicts of pentlandite (Plate XI,a).

Cuproan pentlandite is greyish-pink. Isotropic. Reflectance (R,%) below that of pentlandite: 440nm. - 25.8; 460 - 27.6; 480 - 29.1; 500 - 31.0; 520 - 32.3; 540 - 34.0; 560 - 35.2; 580 - 36.6; 600 - 38.0; 620 - 39.0; 640 - 39.9; 660 - 40.8; 680 - 41.7; 700 - 42.3; 720 - 43.0; and 740 - 43.5.

A characteristic feature of the composition of this mineral (Table 33) is the presence in it of copper which replaces nickel in the structure of pentlandite. Unlike argentopentlandite, the cuproan variety of pentlandite develops from the iron-rich pentlandite variety (Table 33).

X-ray diffraction pattern of this mineral can be readily identified proceeding from the structure of pentlandite. The a=20.27 parameter of its unit cell is considerably greater than that of pentlandite. The principal lines of its X-ray diffraction pattern are as follows: 3.3(113); 2.99(222); 1.99(333); and 1.833(444).

Violarite

Violarite is among the minerals sparsely developed in the Noril'sk ores. It occurs for the most part in intergrowths with pentlandite and develops in chalcopyrite veins by replacing pentlandite [18]. There have been recorded all the stages of replacement from slender borders around the periphery of pentlandite grains to pseudomorphs of violarite in pentlandite. The octahedral cleavage characteristic of pentlandite persists in the pseudomorphs.

TABLE 33

Compositions of argentopentlandite and cuproan pentlandite and of the pentlandite associated with them (weight %, X-ray micro-analysis) p.96

Ores	Sample Numbers	Elements							
		Fe	Ni	Ag	Cu	Co	S	Total	Formula
Massive pyrrhotite-chalcopyrite ores	15082	35.0	21.10	Argentopentlandite 14.0	0.30	0.05	31.30	101.70	$(Fe_{5.14}Ni_{2.95}Cu_{0.04})_{8.13}Ag_{1.07}S_8$
Same as above	15082	32.4	34.0	Pentlandite -	-	0.5	33.2	100.1	$(Fe_{4.48}Ni_{4.48}Co_{0.06})_{9.02}S_8$
Breccioid pentlandite-chalcopyrite ores	16150	32.9	23.20	Argentopentlandite 14.40	0.10	0.01	31.20	101.70	$(Fe_{4.84}Ni_{3.25}Cu_{0.02})_{8.11}Ag_{1.11}S_8$
Breccioid pentlandite-millerite-chalcopyrite ores	13711	29.7	25.90	Argentopentlandite 14.0	0.3	-	31.0	100.9	$(Fe_{4.39}Ni_{3.65}Cu_{0.004})_{8.05}Ag_{1.07}S_8$
Same as above	13711	25.1	41.6	Pentlandite -	0.03	0.31	32.2	99.2	$(Ni_{5.59}Fe_{3.55}Co_{0.039}Cu_{0.004})_{9.18}S_8$
Massive cubanite-talnakhite ores	245	41.2	17.7	Cuproan pentlandite -	7.0	-	33.3	99.2	$(Fe_{5.68}Ni_{2.32}Cu_{0.8})_{8.8}S_8$
Same as above	245	39.0	27.2	Pentlandite -	0.5	-	32.3	99.0	$(Fe_{5.55}Ni_{3.68}Cu_{0.06})_{9.29}S_8$
Massive mooihoekite-cubanite ores	-	41.0	16.4	Cuproan pentlandite -	7.5	-	33.7	98.6	$(Fe_{5.52}Ni_{2.00}Cu_{0.88})_{8.4}S_8$

The second type of the occurrence of violarite is in the form of its complex intergrowths with millerite and nickeloan pyrite in exocontact millerite-chalcopyrite ores impregnated in labrador basalts, where sulphides form spherical grains in place of the carbonate amygdules found there previously. Violarite, mistaken in the past for linnaeite [22], is represented in these intergrowths by platy crystals. The shape of the millerite, nickeliferous pyrite and violarite aggregates and the proportions of these minerals in the intergrowths show that they formed in the process of exsolution of pentlandite [22].

Violarite was described earlier [238 and 274] as a product of supergene alterations of pentlandite. In subsequent works [255 and 256] supergene violarites are differentiated into the violarites evolved from pentlandite and those developed by replacing monoclinic pyrrhotite. The composition of the former correlates with regard to its Ni and Co contents with the composition of primary pentlandite, but the latter is commonly richer in iron and has low Co concentrations. Because of the presence of dessication cracks and porosity, both yield low totals when their composition is determined with the help of a probe. Another characteristic of these minerals is their deviation from the ideal stoichiometry on account of their sulphur deficiency.

The association of the Noril'sk violarite that replaces pentlandite, with carbonate, barite and sphalerite or, less often, galena led us to conclude [18] that it is hypogene in origin. The possibility of its being of a hypogene origin is also supported by experimental studies [195]. The violarite found in intergrowths with millerite and nickeloan pyrite is undoubtedly also hypogene. Hypogene violarites associated with vaesite, pyrite and millerite were recently described from deposits of Western Australia [228].

Analyses of the composition of the Noril'sk violarites support the hypothesis regarding their hypogene origin. They are characterized by a stoichiometric composition (Table 34) corresponding to the formula $(Fe,NiCo)_3S_4$ or, if we take into account their constant content of iron, $Fe(Ni,Co)_2S_4$. The violarite found in ore veins, where it replaces pentlandite, has, p.98 similarly to the latter, a low cobalt concentration in contrast to the violarite intergrown with millerite and nickeloan pyrite that has a higher content of cobalt. X-ray diffraction patterns of the Noril'sk violarites fully coincide with the data obtained for standard violarite.

TABLE 34

Compositions of violarite and of the pentlandite replaced by it (weight %, X-ray micro-analysis)

Ores	Sample Number	Ni	Co	Cu	Fe	S	Total	Formula
					Violarite			
Massive pentlandite-chalcopyrite ores	28/41	37.6	0.57	0.35	18.4	42.2	99.0	$Fe_{1.0}(Ni_{1.945}Co_{0.030}Cu_{0.018})_{1.993}S_4$
					Pentlandite			
Same as above		41.3	0.56	-	25.4	33.0	100.25	$(Ni_{5.466}Fe_{3.537}Co_{0.07})_{9.073}S_8$
					Violarite			
Impregnated millerite-chalcopyrite ores in labrador basalts	158/59	35.4	3.0	0.08	18.6	42.1	99.9	$Fe_{1.014}(Ni_{1.837}Co_{0.155}Cu_{0.03})_{1.995}S_4$

Godlevskite

Godlevskite was initially discovered [104] in association with bornite and millerite in selvages of a chalcopyrite vein from the Noril'sk deposit and in impregnated bornite and chalcopyrite-bornite ores from the Talnakh deposit. Godlevskite was subsequently found in impregnated pentlandite-millerite-heazlewoodite ores from the nickel sulphide deposit at Texmont, Ontario [253], and at other Canadian deposits [220].

In the Talnakh and Noril'sk deposits godlevskite forms small (up to 0.01 mm) or, less often, larger (up to 0.5mm) crystals amidst bornite. Bornite corrodes godlevskite and may form in it small embayments or slender cross veinlets. Allotriomorphic aggregates of godlevskite grains are particularly abundant. Isolated crystalline grains with distinctive lamellar twins displaying "geniculate" bents (Plate XI,b) are found less often; these grains permit us to distinguish godlevskite from millerite and heazlewoodite.

Under the microscope godlevskite is light-yellow with a weak bireflectance in yellowish tints. Anisotropy strong, but weaker than in millerite; pleochroism in tones of bluish to reddish. A feature characteristic of godlevskite is the reversal of the optic sign (560 to 620nm. for different sections). Reflectance (R'_g and R'_p,%): 440nm. - 32.8 and 37.7; 480 - 41.5 and 44.4; 520 - 47.4 and 48.6; 540 - 48.7 and 49.5; 580 - 50.8 and 50.2; 620 - 52.4 and 51.2; 660 - 54.2 and 52.4; 700 - 55.8 and 53.6; 740 - 56.4 and 54.5.

Microhardness of godlevskite ($p=40-50g$) is 382-418kg/mm^2 averaging 397kg/mm^2 (PMT*-3, $H_{NaCl}=21kg/mm^2$). According to the data of Naldrett [253], microhardness of godlevskite from the Texmont Mine is somewhat greater - 464kg/mm^2($p=100g$).

The composition of the Noril'sk and Texmont [253] godlevskites is shown in Table 35. The godlevskite from Noril'sk differs from the Canadian variety in having a higher cobalt content. All the godlevskites are characterized by a small deficiency of metal in the formula relative to the theoretical Ni_7S_6.

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* Transliteration. Translator.

TABLE 35

Composition of the Noril'sk and Canadian godlevskites (weight %, X-ray micro-analysis)

Elements	1	2	3[25.3]	Elements	1	2	3[253]
Ni	62.75	64.26	63.56	Cu	0.13	0.07	-
Fe	3.94	2.71	3.65	S	33.15	32.32	32.24
Co	1.69	0.56	0.07	Total	101.67	99.92	99.52

1 and 2-Noril'sk godlevskites: 1-$(Ni,Fe,Co)_{6.80}S_6$ and 2-$(Ni,Fe,Co)_{6.86}S_6$; 3-Godlevskite from the Texmont deposit (Canada) - $(Ni,Fe)_{6.85}S_6$.

X-ray studies on godlevskite were done by the single-crystal method. It has been established that the mineral has a non-centered rhombic unit cell and belongs to one of the four space groups: C222, Cmm2, Cm2m or Cmmm. According to the X-ray rotation patterns, its unit cell parameters are a=9.180±0.003, b-11.263±0.003 and c=9.457±0.003Å. X-ray diffraction pattern of this mineral has 64 lines and is identical to that of the low-temperature δ-Ni_7S_6[104]. The principal lines of the X-ray diffraction pattern are: 5.75(2) (111); 4.70(1) (002); 4.14(2) (201); 3.62(2) (022); 3.28(5) (131); 2.85(10) (222); 2.80(2) (132); 2.75(2) (023); 2.33(4) (241); 2.10(5) (204); 1.906(3) (333); 1.832(8) (234); 1.803(9) (044); 1.795(8) (025); 1.654(8) (530); 1.625(3) (262); 1.478(2) (385); 1.176(2) (661); 0.980(4) (557).

Hauchecornite

p.99

Hauchecornite was identified in veinlet-impregnated chalcocite-bornite galena-rich ores from the upper exocontact of the Okryabr'skii deposit of massive chalcopyrite ores [91]. It had previously been unknown in deposits of the USSR. Hauchecornite forms elongated, often tabular rectangular crystals measuring 5-10x30 to 200x700μm amidst galena, bornite and chalcocite (Plate XI,c). In reflected light hauchecornite has a creamy-pink colour and a weak bireflectance. Moderately high magnitude of reflectance (R_g,%): 440 nm. - 38.0; 460 - 39.9; 480 - 41.6; 500 - 43.1; 520 - 44.5; 540 - 46.0; 560 - 47.0; 580 - 47.9; 600 - 49.1; 640 - 49.4; 660 - 49.9; 680 - 50.2; 700 - 50.8; 720 - 51.0 and 740 - 51.7. At crossed nicols the mineral is generally moderately anisotropic with occasional weakly anisotropic sections.

Indentation hardness of hauchecornite varies from 360 to 392 averaging 375km/mm^2 (6 measurements).

The composition of the mineral (MAP*-2; V.D. Begizov, analyst) determined for two grains proved to be quite close (in wt %): Ni - 43.8 and 43.6; Bi - 33.6 and 22.9; S - 21.5 and 21.4; Co - 0.7 and 0.8; Fe - 0.2 and 0.2; As - 0.6 and 0.5. Their respective empirical formulas $(Ni_{8.90}Co_{0.14}Fe_{0.04})_{9.08}\cdot(Bi_{1.92}As_{0.09})_{2.01}S_8$ and $(Ni_{8.90}Co_{0.16}Fe_{0.04})_{9.10}(Bi_{1.94}As_{0.08})_{2.02}S_8$, are very close to the theoretical formula $Ni_9Bi_2S_8$. The characteristic compositional features of the hauchecornite analysed by us are the absence of antimony and tellurium, and the virtual absence of arsenic, all of which are characteristic components of hauchecornites from other deposits [205].

The X-ray pattern of hauchecornite from the Oktyabr'skii deposit is practically identical to the standard pattern. It comprises 46 lines, the strongest ones among which are 4.34(6); 3.67(5); 2.80(10); 2.40(6); 2.32(6); 1.867(8); 1.808(4); and 1.730(4). Parameters of the tetragonal /cell/unit/ a=14.65±0.01 and c=10.76±0.01Å.

Parkerite

Parkerite had been unknown in deposits of the Noril'sk region until its discovery at the Oktyabr'skii deposit in galena-rich veinlet-impregnated chalcocite-bornite ores from the upper exocontact of massive ores with increased copper contents [92].

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* Transliteration. Translator.

Very small (maximum 20-30mm in diameter) spherical, sometimes elongated crystals of parkerite are found only in galena (Plate X,d). Under the microscope parkerite displays a perceptible bireflectance with the colour changing from pure white to light grey of a delicate olive shade, and a marked anisotropy revealing the twin structure of its grains.

Parkerite has a higher reflectance magnitude than galena (R,%): 440 nm.- 49.5; 460 - 49.0; 480 - 48.8; 500 - 48.3; 520 - 48.9; 540 - 49.1; 560 - 52.0; 700 - 52.9; 720 - 53.0 and 740 - 53.2. Indentation hardness varying from 119 to 138 and averaging 127 kg/mm^2.

The composition of parkerite (JXA - 50-A; V.K. Garanin, analyst) is as follows (wt %): Ni - 28.81; Bi - 62.88; Pb - 1.30; S - 9.27; total 102.26. Its empirical formula $Ni_{3.16}(Bi_{1.94}Pb_{0.04})_{1.98}S_{1.86}$ is close to the stoichiometric formula $Ni_3Bi_2S_2$.

Covellite

Covellite is found rarely in these ores. Its small platy crystals have been observed in bornite veins near the cracks and around the carbonate veinlets cutting across bornite.

Tetrahedrite

Tetrahedrite had not been previously encountered in deposits of copper-nickel ores. Extremely rare grains of tetrahedrite have been identified in carbonate veinlets and carbonate-chlorite zones intersecting massive pyrrhotite ores [51]. It forms small, irregularly shaped agglomerations encrusting minerals of the loellingite-safflorite-rammelsbergite series.

Chemical composition of tetrahedrite (wt %): Cu - 38.3; Zn - 7.8; Fe - 0.2; Sb - 29.6; As - 1.6; S - 23.2; total 100.7.

Principal lines of the X-ray diffraction pattern: 2.98 (10); 2.61(2); 2.35(2); 1.867(3); 1.833(3) and 1.568(3). p.100

Stannite

Identified by V.D. Begizov in massive mooihoekite ores enriched in galena, in association with altaite, hessite and minerals of platinum metals. According to V.D. Begizov's data (personal communication), the composition of stannite is as follows (wt %): Cu - 30.0; Fe - 13.4; Sn - 27.9; S - 29.4; total 100.7. This composition gives us the empirical formula $Cu_{2.03}Fe_{1.03}\cdot Sn_{1.01}S_{3.93}$ that is close to the stoichiometric formula.

Djerfisherite

This compound chlorine-containing iron-copper-nickel sulphide was found for the first time on Earth in the ores from the Talnakh deposit [31]. Prior to that it was identified in meteorites [204 and 201]. Djefisherite was subsequently detected in pegmatites from the Khibines [136], in skarns from Tazheran [96] and in kimberlites from Yakutia [63] and South Africa [193]. As a result of structural analyses [62] it was discovered that the initial formula of djerfisherite $K_3Cu(Fe,Ni)_{12}(S,Cl)_{14}$ [204] had to be changed to $K_6(Fe,Cu,Ni)_{24}S_{26}Cl$.

Djerfisherite forms the largest agglomerations (measuring up to 1mm) in deposits of massive cubanite-talnakhite ores. They are confined to cubanite, in which djerfisherite is represented by irregularly shaped grains or (less often) by grains with regular boundaries. Regularly oriented trigonal sections of djerfisherite grains have been observed in talnakhite. Djerfisherite borders in pentlandite are equally characteristic. These borders evolve as a result of the replacement of pentlandite by djerfisherite at the boundary of its porphyritic crystals with talnakhite. The association of djerfisherite with other minerals of talnakhite ores that is worth mentioning is the formation around its grains of fringes composed of a later sphalerite or some platinum minerals (Plate XII,a).

In the rocks enclosing gabbro-dolerite intrusions djerfisherite has been encountered amidst pyrrhotite and pyrrhotite-chalcopyrite impregnated ores. It replaces chalcopyrite and pyrrhotite and forms borders at the contact of sulphide crystals with pyroxenes and other silicates. Moreover, it may be separated from pyrrhotite by a slender fringe of secondary pentlandite (Plate XII,b). In apopericlase brucite rocks djerfisherite and valleriite substituting for pyrrhotite, are found in the interstices between the spherical brucite crystals.

Djerfisherites from massive and impregnated ores, respectively, differ markedly in properties and composition. Djerfisherite is isotropic, but in massive talnakhite ores it is olive-brown in colour, whereas in impregnated pyrrhotite ores it is pinkish-brown. These djerfisherites also differ in reflectance (R,%): 440nm.-17.7 and 17.7; 480 - 19.6 and 19.2; 520 - 21.4 and 21.5; 540 - 22.4 and 22.8; 580 - 23.7 and 25.1; 620 - 24.5 and 27.2; 660 - 25.4 and 29.0; 700 - 25.8 and 30.4; 740 - 25.9 and 31.4.

Analysis of the composition of djerfisherite (Table 36) shows significant variations in its contents of copper, iron and nickel. Cuproan djerfisherite is the variety typical of talnakhite ores. The pentlandite intergrown with djerfisherite is enriched in iron and contains copper. The djerfisherite found in impregnated pyrrhotite ores is represented by a copper-poor nickeloan variety. Its content of nickel is up to 21.5, i.e. higher than that of the compositionally similar djerfisherites from kimberlites [63]. The pentlandite forming borders around this djerfisherite, is enriched in nickel and cobalt, small concentrations of which have also been detected in the djerfisherite (Table 36). It may thus be seen that compared to the meteoric djerfisherite with the general formula $K_6F_{24}S_{26}Cl$, the djerfisherites of the Noril'sk ores are of the cuproan $K_6(Fe,Cu)_{26}S_{26}Cl$ (with Co up to 16.58%, Cu Fe) or nickeloan $K_6(Fe,Ni)_{22-26}Cl$ (with Ni up to 21%, Ni Fe) type.

These compositional differences are also reflected in the X-ray diffraction patterns of djerfisherite. Its cuproan variety has larger primitive unit cell parameters and respectively greater interplanar distances of the principal reflections than those of its nickeloan modification: 10.41; 10.31Å; (111) - 6.05; 5.95; (311) - 3.17; 3.10; (222) - 3.03; 2.96.

p.101

TABLE 36

Compositions of djerfisherites from the Noril'sk ores and of the pentlandite associated with them (weight %, X-ray microanalysis)

Ores	K	Fe	Cu	Ni	Co	S	Cl	Total
Massive talnakhite ores	8.98	39.22	16.58	1.48	-	31.75	1.34	99.35
djerfisherite	-	38.7	0.28	28.2	0.45	33.6	-	101.23
Veinlet-impregnated exocontact ores								
djerfisherite	9.5	36.8	3.6	14.1	-	34.4	1.5	99.9
"	9.5	35.7	1.0	18.5	-	34.6	1.5	100.8
Brecciated ores								
djerfisherite	9.5	31.8	1.7	21.0	0.11	35.6	1.53	101.24
pentlandite	-	25.6	0.03	37.1	4.7	33.0	-	100.43
Djerfisherite from meteorite [204]	8.7	50.7	4.2	0.8	-	33.8	1.0 Na-0.3	99.5

Shadlunite

Shadlunite was discovered originally in pentlandite-cubanite-talnakhite ores from Talnakh and in pentlandite-cubanite-mooihoekite ores from the Oktyabr'skii deposit [67]. It occurs in the ores in the form of irregularly shaped grains measuring hundredth fractions of a millimetre to 0.3-0.4mm, and in veinlets 0.1mm or less in width. It is found most often amidst cubanite, sometimes in talnakhite or mooihoekite, and rarely in pentlandite.

Shadlunite in association with sphalerite (forming borders around shadlunite), galena, native silver and plumbopalladinite is confined in the Talnakh ores to veinlet-like agglomerations of cubanite that evolves by replacing talnakhite. There have also been recorded finds of shadlunite in the form of small (0.03-0.06mm) oval inclusions in djerfisherite [31].

The variety characteristic of mooihoekite ores is Mn shadlunite which forms small grains or slender veinlets cutting across mooihoekite, pentlandite and cubanite (Plate XII,c). There have been observed graphic myrmekite intergrowths of shadlunite with pentlandite, which it replaces. Alabandite has often been encountered in these ores alongside Mn-shadlunite [34]. There have been reported instances of valleriite replacing Mn-shadlunite, but in some cases valleriite contains well-formed small crystals of Mn-shadlunite.

In reflected light shadlunite is greyish-yellow and weakly anisotropic; at crossed nicols its grains display polysynthetic twinning. Reflectance (R,%) for 440, 460, 480, 500, 520, 530, 560, 580, 600, 620, 640, 660, 680, 700, 720 and 740 nm. for shadlunite and Mn-shadlunite (the first and the second figure, respectively): 19.0 and 21.2; 20.1 and 22.7; 20.9 and 24.7; 22.5 and 26.5; 23.4 and 27.9; 24.8 and 29.0; 25.8 and 29.9; 26.8 and 30.8; 27.5 and 31.2; 28.3 and 32.3; 29.1 and 32.9; 30.0 and 33.8; 30.8 and 34.5; 31.0 and 34.6; 31.3 and 35.2; and 31.3 and 35.2.

Reflectance of Mn-shadlunite is higher throughout the interval. The hardness of shadlunite and Mn-shadlunite measured with IMT*-3 ($H_{NaCl}=21 kg/mm^2$ at $P=5$) at a load of 20g is $210 kg/mm^2$ (on the basis of seven measurements for shadlunite) and $195 kg/mm^2$ (on the basis of five measurements for Mn-shadlunite), respectively.

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* Transliteration. Translator.

The chemical composition of shadlunite (Table 37) analysed with the help of a "Kameka" electron-probe, is characterized by constant copper and iron contents and by variable concentrations of lead, manganese and cadmium.

A.M. Karpenkov [82] mentions a shadlunite with the concentration of cadmium up to 9.1 wt %. There may be discovered shadlunites with even greater contents of manganese and cadmium than those mentioned above or even with "end-member" compositions $(Cu,Fe)_8PbS_8$, $(Cu,Fe)_8MnS_8$ and $(Cu,Fe)_8CdS_8$. p.102

TABLE 37

Chemical composition of shadlunite (wt %, X-ray micro-analysis)

Elements	Shadlunite		Mn-shadlunite			
	wt.%	atomic quantities	wt.%	atomic quantities	wt.%	atomic quantities
Cu	27.5	0.433	29.8	0.469	31.19	0.490
Fe	24.1	0.432	26.4	0.473	27.21	0.487
Pb	16.6	0.080	8.2	0.040	4.8	0.023
Mn	-	-	3.2	0.058	4.6	0.084
Cd	3.9	0.035	1.3	0.012	1.0	0.009
S	27.4	0.854	29.4	0.917	31.46	0.979
Total	99.5		98.3		100.26	
Σ Me:S		9.18:8		9.18:8		8.92:8
Formula	$(Cu,Fe)_{8.1}(Pb,Cd)_{1.08}S_8$		$(Cu,Fe)_{8.22}(Mn,Pb,X\ Cd)_{0.96}S_8$		$(Cu,Fe)_{7.97}(Mn,Pb,X\ Cd)_{0.95}S_8$	

The similarity of the debyeograms obtained for shadlunite to that of pentlandite enabled us to identify the debyeogram of shadlunite in the cubic unit cell Fm3m with a=10.91Å (shadlunite) and a=10.73Å (Mn-shadlunite).

The interplanar distances, intensities and hkl of shadlunite (λ Fe without the filter, RKD* - 57.3) are: 5.42(3); (002); 3.84(4)(220); 3.29(10)(131); 3.16(2)(222); 2é72(1)(400); 3.45(1)(240); 2.23(1)(422); 2.11(4)(333, 115); 1.925(9)(440); 1.845(I)(135); 1.666(2)(533); 1.575(1)(444); 1.424(2)(731)(553); 2359(1)(800); 1.292(1)(660); 1.147(I)(139); 1.115(1) (448) and 1.105(1)(771).

Iron and copper atoms are statically arranged in tetragonal positions 32(f) (XXX, $X \sim 0.125$), while larger atoms, i.e. those of lead, manganese and cadmium, occupy the centres of the octahedral 4(c)$(\frac{1}{2}\ \frac{1}{2}\ \frac{1}{2})$.

Hawleyite

Thin (10-20μm) veinlets of zinc-containing hawleyite have been encountered in association with cadmium-rich sphalerite in massive mooihoekite ores. This mineral had previously been unknown at copper-nickel deposits. The zinc-containing hawleyite may be a hypogene product formed as a result of the accumulation of cadmium in residual fluids during the crystallization of the sulphide melt. This is supported by its association with hypogene fluids and by the absence of any signs of oxidation in the latter.

In reflected light hawleyite is similar to sphalerite, but has a more intensive bluish tinge. At crossed nicols it is isotropic; no internal reflections have been observed. Hawleyite has a higher reflectance than sphalerite. but the shape of the spectrum remains the same. (R,%): 440nm. - 23.0; 460 - 21.8; 480 - 21.0; 500 - 20.1; 520 - 19.4; 540 - 19.0; 560 - 18.6; 580 - 18.3; 600 - 18.0; 640 - 17.8; 660 - 17.7; 680 - 17.5; 700 - 17.6; 720 - 17.7 and 740 - 17.8. Its indentation hardness is also greater than that of sphalerite and is equal to 304k/mm^2 (the average of four measurements).

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* RKD is probably the make of the camera used. Translator.

The elements identified in the composition of hawleyite are the same as in sphalerite (Table 38).

TABLE 38

Composition of zinc-containing hawleyite (wt %, X-ray, microanalysis)

Sample Number	Cd	Zn	Fe	Cu	Mn	Ni	Co	S	Total
K-31	43.68	23.27	4.08	2.35	0.4	0.01	0.01	25.83	99.26
K-32	45.24	22.99	4.16	1.65	0.4	0.01	0.01	25.93	99.98
K-33	47.70	23.71	3.95	1.18	0.4	0.01	0.01	25.69	102.23

Formula

K-31 - $(Cd_{0.18}Zn_{0.44}Fe_{0.09}Cu_{0.05}Mn_{0.01})_{1.07}S$

K-32 - $(Cd_{0.50}Zn_{0.43}Fe_{0.09}Cu_{0.03}Mn_{0.01})_{1.06}S$

K-33 - $(Cd_{0.53}Zn_{0.45}Fe_{0.09}Cu_{0.02}Mn_{0.01})_{1.1}S$

Alabandite

p.103

Alabandite, a sulphide of manganese, had previously been unknown in copper-nickel deposits. We discovered it in cubanite-mooihoekite ores of the Oktyabr'skii deposit [34]. Alabandite forms thin (up to 0.01mm) and short (1-2mm) veinlets in mooihoekite, cubanite and pentlandite, as well as larger irregularly shaped agglomerations (up to 0.5mm) and metacrysts in porphyritic pentlandite.

Alabandite associates with manganese-ferruginous carbonate of the type of oligonite, and is surrounded by borders of pentlandite with up to 0.48 wt % of manganese. Here and there it is accompanied by chains of small galena, sphalerite or manganese-containing shadlunite crystals (Plate XII,d). The products of exsolution contained in it are platy inclusions of chalcopyrite. Alabandite is intersected by veinlets of native silver. Under the microscope it is bluish-grey, lighter than sphalerite.

Isotropic. Reflectance (R,%): 440nm. - 25.4; 480 - 23.9; 520 - 23.4; 560 - 22.8; 600 - 22.3; 640 - 22.0; 680 - 21.8; and 720 - 21.5.

Compositional determinations of the mineral with the help of a microprobe yielded the following data: Mn - 55.0 wt.%, Fe- 2.0; Cu - 5.6; and S-34.4. The increased copper content is probably due to the presence of chalcopyrite inclusions.

The calculated formula of the mineral is close to the theoretical formula of manganese monosulphide.

The principal lines of the X-ray diffraction diagram are: 2.614(10) (002); 1.846(9) (0.22); 1.170(6) (024); and 1.067(5) (224).

Molybdenite

At copper-nickel deposits there have been recorded only single finds of molybdenite [160,153 and 166]. At the Talnakh deposit molybdenite has been encountered in massive talnakhite-cubanite ores, where minutest elongated grains of that mineral (30x100µm) are closely intergrown with sphalerite and are confined to microcracks in sulphides filled with calcite [89]. Molybdenite overgrows cubanite and corrodes it. Judging from their correlation and from the fact that molybdenite is confined to calcite and associates with sphalerite, molybdenite formed after the crystallization of the principal ore-forming sulphides.

In reflected light molybdenite has a strong bireflectance with the colour changing from white-blue in the maximum position to grey at the minimum. The mineral is strongly anisotropic. Reflectances (Rm and Rp%) 440nm. - 59.5 and 26.9; 460 - 58.3 and 26.5; 480 - 56.7 and 25.8; 500 - 53.6 and 24.8; 520 - 51.8 and 24.0; 540 - 50.2 and 23.2; 560 - 49.1 and 22.8; 580 - 48.0 and 22.1; 600 - 47.5 and 21.8; 620 - 48.0 and 21.8; 640 - 48.9 and 21.7; 660 - 48.6 and 21.4; 680 - 47.9 and 21.2; 700 - 49.1 and 20.8; 720 - 48.1 and 21.1; and 740 - 47.0 and 21.3, are very close to the Rm and Rp of the hexagonal 2H-modification of molybdenite.

The distinctive feature in the composition of this molybdenite is its very high concentration of rhenium, the highest ever recorded in a natural molybdenite (Mo-56.7 and 58.0; Re-3.8 and 2.4; S-39.4 and 39.3; total - 99.9 and 99.7%, respectively). It is characteristic that rhenium is distributed within the molybdenite grain in zones: its maximum concentrations are confined to the centre of the grain (3.8%Re); the next zone has 2.4%Re; and lastly the content of that element in the peripheral border is only 0.6%.

Thalcusite

This new sulphide of thallium, copper and iron was discovered in galena-rich cubanite-chalcopyrite ores at the Talnakh deposit in association with minerals of platinum metals, i.e. altaite, sphalerite and shadlunite [90]. It forms platy, often markedly elongated (Plate XII,e), or sometimes spherical isometric crystals in galena, chalcopyrite and cubanite and is confined to the boundaries of these minerals. Cleavage parallel to the elongation. Most of the grains of this mineral measure 10-15μm in diameter and only isolated single grains attain 40x150μm.

Under the microscope thalcusite has a weak bireflectance with the colour changing from light grey to dark grey, and a p.104
moderate magnitude of reflectance (Rg' Rp'%): 440nm. - 30.7 and 29.3; 460 - 31.3 and 30.4; 480 - 30.1 and 29.6; 500 - 30.8 and 29.8; 520 - 30.8 and 29.7; 540 - 29.9 and 28.4; 560 - 29.8 and 27.9; 580 - 30.3 and 27.9; 600 - 30.3 and 28.4; 620 - 32.1 and 29.2; 640 - 33.0 and 29.7; 660 - 33.7 and 30.6; 680 - 34.5 and 30.7; 700 - 35.9 and 31.7; 720 - 36.4 and 32.0;and 740 - 37.4 and 33.0. At crossed nicols it is anisotropic with pleochroic effects from light yellow to dark grey.

Brittle mineral foliating into thin flakes. Indentation hardness 82-92, averaging $88kg/mm^2$.

It has been determined that the composition of thalcusite is as follows (wt %): Tl - 52.2; 53.4; Cu - 22.6; 20.5; Fe - 9.1; 9.9; S - 16.3; 16.5; total - 100.3 and 100.3. Its formulas are $Cu_{2.79}Tl_{2.01}Fe_{1.28}S_4$ and $Cu_{2.51}Tl_{2.03}Fe_{1.37}S_4$ or, in a general form, $Cu_{3-x}Tl_2Fe_{1+x}S_4$.

The parameters of the tetragonal unit cell of thalcusite are a=3.882 and c=13.25Å. The strongest lines in its X-ray diffraction pattern are: 3.73(8) (101); 3.31(4)(004); 2.91(10)(103); 2.53(10)(112); 2.18(4)(105); 1.941(5)(200); and 1.717(5)(116).

With regard to its physical properties, chemical composition and structure thalcusite is very close to bukovite, a selenide of thallium, copper and iron. These minerals may be isostructural.

Galenoclausthalite and clausthalite

These minerals are the first selenides identified in copper-nickel deposits [86]. Galenoclausthalite and clausthalite are characteristic of exocontact veinlet-impregnated bornite-millerite-chalcopyrite ores. Galenoclausthalite is also found in impregnated troilite-cubanite-chalcopyrite ores. In exocontact ores the selenides occur in chalcopyrite and bornite forming intergrowths or chains of grains with tellurides of palladium, (Pd,Pt) (Pb,Bi) (S,Se) and native silver. Clausthalite occurs right next to the grains of tellurides or overgrows them; galenoclausthalite is commonly found in bornite and chalcopyrite or amidst the gangue, at a certain distance from the concentrations of tellurides. In impregnated ores galenoclausthalite associates with paolovite, tellurian sobolevskite, moncheite and native silver.

These minerals occur in the form of spherical or xenomorphic grains with undulate outlines; the grains commonly measure 5-30μm in diameter and do not exceed 160μm. In reflected light it is difficult to distinguish galenoclausthalite from clausthalite: both minerals are isotropic and differ from galena because of their clear bluish tint (particularly against the background of bornite and chalcopyrite) and greater reflectance values [86]. The best way to determine the differences between galenoclausthalite and clausthalite is by analysing their compositions (Table 39).

TABLE 39

Composition of galenoclausthalite and clausthalite (weight %, X-ray micro-analysis)

Sample Number	Pb	Se	S	Total	Empirical Formula
9811	79.0	12.2	7.0	98.2	$Pb_{1.02}(Se_{0.42}S_{0.58})$
9251/3	79.1	14.9	6.2	100.2	$Pb_{1.02}(Se_{0.19}S_{0.51})$
19182	78.5	15.5	5.5	99.5	$Pb_{1.03}(Se_{0.53}S_{0.17})$
9114	76.4	16.5	5.1	98.0	$Pb_{1.00}(Se_{0.57}S_{0.13})$
9251/13	74.6	24.9	1.4	100.9	$Pb_{1.01}(Se_{0.88}S_{0.12})$

FOOTNOTE. Samples 9118, 9114 and 9251---veinlet-impregnated bornite-millerite-chalcopyrite ores; sample 19182---impregnated troilite-cubanite-chalcopyrite ores

We refer to galenoclausthalites the minerals containing 33 to 66 mol.% PbSe, and to clausthalite those containing over 66 mol.% PbSe [85].

Altaite

Altaite is fairly common in all the types of ores. In impregnated ores small (20-30μm) altaite crystals intergrown with p.105 paolovite occur amidst chalcopyrite. In massive pyrrhotite ores minutest xenomorphic altaite grains are associated with platinum group minerals forming xenomorphic inclusions or veinlet-like agglomerations in them. In massive ores composed essentially of chalcopyrite (talnakhite, mooihoekite), altaite commonly overgrows aggregates of froodite, niggliite and paolovite grains or occurs in the form of very small (2-3μm) xenomorphic crystals amidst the sulphides. The largest altaite concentrations have been encountered in massive and veinlet-impregnated chalcocite-bornite exocontact ores with increased contents of galena.

Altaite is represented in these formations by three morphological varieties: small (a few microns) regular inclusions in galena (Plate XII,f), large (up to a few millimetres) isolated grains gravitating towards the galena-chalcopyrite boundaries, and fairly large crystals intergrown with hessite, tellurian sobolevskite, moncheite and other minerals of platinum or palladium.

Altaite has very characteristic optic properties: a high reflectance (R,%) 440nm. - 58.7; 460 - 60.9; 480 - 63.1; 900 - 66.3; 520 - 67.3; 540 - 68.4; 560 - 68.0; 580 - 66.9; 600 - 65.5; 620 - 64.3; 640 - 63.0; 660 - 61.8; 680 - 60.2; 70 - 58.9; 720 - 57.9 and 740 - 56.7, and a bright white colour with a greenish tint. Isotropic at crossed nicols. Indentation hardness 56kg/mm^2 (average from five measurements).

In some grains of altaite there have been detected minor quantities of copper, antimony and sulphur in addition to tellurium and lead (Table 40).

The debyeogram of the altaite from the Talnakh deposit is identical to the standard debyeogram of that mineral.

TABLE 40

Composition of altaite from different types of ores (weight %, X-ray micro-analysis)

Sample number	Pb	Te	S	Cu	Sb	Total
0-4/3	59.8	36.4	n.d.*	n.d.	n.d.	96.2
14048	60.0	37.3	" "	0.2	0.2	97.7
I-1973	62.0	36.3	0.40	n.d.	n.d.	98.7

Formula

0-4/3 - $Pb_{0.996}Te$

14048 - $(Pb_{0.992}Cu_{0.001})_{0.993}(Te_{0.999}Sb_{0.001})$

I-1973 - $Pb_{0.10}(Te_{0.96}S_{0.04}$

FOOTNOTE. 0-4/3 --- Massive pyrrhotite ores; 14048---Massive cubanite-chalcopyrite ores; I-1973---A platy altaite crystal in galena from massive galena-rich chalcopyrite ores.

*n.d. - not detected

ARSENIDES, SULPHOARSENIDES, ANTIMONIDES AND SULPHOANTIMONIDES OF NICKEL, COBALT AND IRON

The first finds of nickeline, maucherite, gersdorfite and breithauptite from the Noril'sk ore region are described in brief in V.M. Izoitko's work [79]. Subsequent analyses of the ores allowed us to identify more minerals from these groups [57].

Arsenides, sulphoarsenides, antimonides and sulphoantimonides of nickel, cobalt and iron form a characteristic mineral association comprising nickeline, maucherite, safflorite, loellingite, rammelsbergite, gersdorfite, breithauptite and ulmanite. They are found together with native arsenic, tetrahedrite, as well as pyrite, pentlandite, galena, sphalerite, chalcopyrite, pyrrhotite, bornite, chalcocite and nonmetallic minerals (calcite, chlorite and, rarely, fluorite) and are confined to carbonate veins, carbonate-chlorite zones and bornite or bornite-chalcocite veinlets cutting across massive pyrrhotite ores at the Talnakh p.106 deposit.

The minerals examined rarely form monomineral agglomerations and are commonly found in zoned polymineral intergrowths. There have been distinguished two types of zonal aggregates. The first type is represented by intergrowths with the central part composed of maucherite that is overgrown successively by nickeline, gersdorfite or safflorite and loellingite (Plate XIII,a). There have been observed zoned aggregates in which maucherite is surrounded by nickeline, while the outer part is composed of breithauptite or gersdorfite. Binary mineral intergrowths of nickeline and breithauptite have been encountered less often; the latter mineral may contain veinlet-like agglomerations of ulmanite.

The second type of zonal aggregates is represented by intergrowths of minerals of the loellingite-safflorite-rammelsbergite series with native arsenic or, less often, tetrahedrite. The most characteristic forms of intergrowths are shown in Plate XIII b-d. The stellular grains of loellingite in the central part of the aggregates are surrounded by a granular mass of native arsenic. The next zone is composed of calcite and is succeeded by aggregates of idiomorphic safflorite and loellingite crystals.

Nickeline

Nickeline is one of the most widely distributed minerals of the association examined. It rarely forms monomineral agglomerations and occurs much more frequently in intergrowths with maucherite, loellingite, safflorite and breithauptite or, less often, with ulmanite.

Minor concentrations of cobalt and iron totalling up to 6 atom % (Table 41), have been identified in the composition of this mineral in addition to nickel. The three elements are evenly distributed within individual grains and a sharp increase in the content of cobalt has been recorded only at the contact of nickeline with safflorite.

TABLE 41

Chemical composition of nickeline, maucherite, gersdorfite, breithauptite and ulmanite (weight %, X-ray micro-analysis)

Ni	Co	Fe	Cu	As	S	Sb	Total	Formula
						Nickeline		
41.1	1.6	0.8		51.6		5.8	100.8	$(Ni_{0.91}Co_{0.01}Fe_{0.02})_1(As_{0.94}Sb_{0.06})_1$
41.0	1.2	0.6		48.3		10.3	101.4	$(Ni_{0.96}Co_{0.02}Fe_{0.02})_1(As_{0.89}Sb_{0.11})_1$
						Maucherite		
51.0				42.2	2.0	3.7	98.9	$Ni_{11}(As_{7.13}S_{0.79}Sb_{0.38})_{8.3}$
49.6	2.0			47.0		1.9	100.5	$(Ni_{10.6}Co_{0.1})_{11}(As_{7.86}Sb_{0.20})_{8.06}$
51.0				44.8	0.4	3.7	101.1	$Ni_{11}(As_{7.5}S_{0.2}Sb_{0.4})_{8.1}$
						Gersdorfite		
33.0	1.2	1.0		41.8	18.8	4.0	99.8	$(Ni_{0.91}Co_{0.93}Fe_{0.93})_1(As_{0.93}Sb_{0.06})_{0.99}S_{0.98}$
						Breithauptite		
34.1	0.1		0.3	1.2	1.3	64.1	101.0	$(Ni_{0.99}Cu_{0.01})_1(Sb_{0.91}S_{0.06}As_{0.03})_1$
						Ulmanite		
28.6				2.3	15.4	54.3	100.6	$Ni_1(Sb_{0.91}As_{0.06})_{0.97}S_{0.98}$
27.7				2.2	14.3	57.0	101.2	$Ni_1Sb_1(S_{0.95}As_{0.06})_{1.01}$
27.2		0.2		4.0	13.2	56.1	100.5	$(Ni_{0.00}Fe_{0.01})_1Sb_1(S_{0.89}As_{0.11})_1$

FOOTNOTE. The atomic ratios of the components were calculated from the total of cations taken as equal to the theoretical number of atoms in the formula unit.

Antimony, concentrations of which may attain 11 atom % (Table 41), is distributed unevenly in nickeline. Antimony-rich loci and those relatively poor in antimony form zones parallel to the boundaries of the nickeline grains.

The principal lines of the X-ray diffraction pattern of nickeline are as follows: 2.68(10), 1.973(10), 1.818(8), 1.482(4), 1.338(5), 1.080(7) and 1.040(7). p.107

Maucherite

Maucherite is close in abundance to nickeline, with which it is often intergrown. Apart from nickeline, the minerals found in association with maucherite are loellingite, safflorite, breithauptite and ulmanite. All these minerals form zonal aggregates of intergrown grains with maucherite composing the central loci. Maucherite has also been identified in the bornite veinlets diverging off the chalcopyrite veins at the Noril'sk deposit.

It forms veinlet-like agglomerations of bizzare outlines or borders at the boundary of bornite with carbonate inclusions.

This mineral has a relatively constant chemical composition within individual grains (Table 41). Its maximum cobalt concentration is up to 2.0 wt %. Maucherite has relatively high antimony concentrations (up to 3.7 wt %) and varying sulphur contents (0 to 2.0 wt %).

The principal lines in the X-ray diffraction pattern of maucherite are as follows: 2.98(5); 2.69(10); 2.36(5); 2.23(5); 2.02(10); 1.892(6); 1.715(10); 1.450(4); 1.213(5); and 1.106(5).

Loellingite-safflorite-rammelsbergite

Minerals of the series loellingite-safflorite-rammelsbergite have been encountered in intergrowths with maucherite, nickeline, breithauptite and native arsenic (Plate XIII,a-d). They form zoned aggregates with these minerals and compose their marginal part. Minerals of this series have also been observed in calcite veinlets, where they occur in the form of idiomorphic stellular crystals.

Among the natural diarsenides of the $FeAs_2$ - $CoAs_2$ - $NiAs_2$ system there has been established a large number of intermediate varieties [258, 261 and 14]. Diarsenides from the Noril'sk ore field significantly expand, however, the field of the known natural solid solutions of diarsenides (fig. 22).

Fig. 22

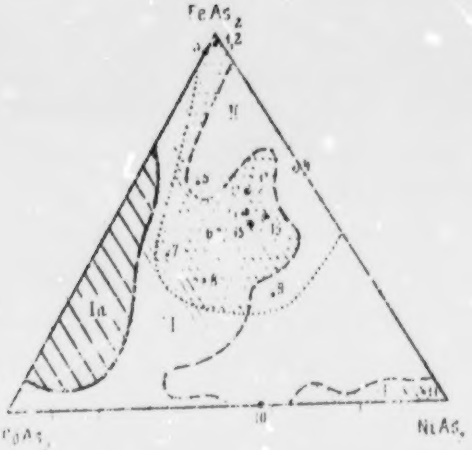

Diagram of the compositions of diarsenides from the series loellingite-safflorite-rammelsbergite.
I-II---compositional fields: I-of diarsenides from the deposit at Cobalt, Ontario [261]; Ia-of the most widely distributed diarsenides; II-of diarsenides from the Noril'sk ore region; 1-16---numbers of the analyses shown in Table 42.

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Isomorphism of cations of the Noril'sk diarsenides is characterized in Tables 42 and 43 and in Plate XIII,e-g. There have been established several distribution patterns of the elements. The first type of distribution (Table 43,A) corresponds to the compositions in which the loellingite minal predominates. Iron is replaced by nickel and cobalt in different quantitative correlations. There have been identified loci, where nickel and cobalt are simultaneously substituted for iron (types B and C) and those where iron is replaced by cobalt alone (type D).

Wide-spread anion isomorphism. A portion of arsenic atoms is replaced by sulphur and antimony in almost all the varieties of diarsenides. The maximum sulphur concentrations attain 10 wt % or 28 atom % of the total anions, and those of antimony 5.8 wt % or 12.5 atom % (Table 42). Compositions with such high concentrations of sulphur have never been detected in nature before. Loci with varying sulphur concentrations form discrete microzones that are parallel to crystallographic outlines of the grains (Plate XIII,g).

Gersdorfite

Gersdorfite occurs in association with nickeline and maucherite and forms zonal aggregates with these minerals. Maucherite with nickeline or nickeline alone composes the central part of these aggregates, and gersdorfite forms their outer border.

This mineral has a stable chemical composition. There have only been observed small-scale variations in the contents of its trace elements, i.e. iron, cobalt and antimony (Table 41). p.108

Breithauptite

Breithauptite, an antimonide of nickel, composes the outer zone surrounding nickeline and maucherite in zonal aggregates and may also be found, though less often, in the form of discrete agglomerations. Ulmanite occurs very rarely in intergrowths with breithauptite; when present, it forms borders and veinlet-like concentrations in the latter. In rare instances there has been identified gersdorfite in intergrowths with breithauptite.

No significant variations have been detected in the chemical composition of breithauptite (Table 41). Its trace elements are cobalt and copper amounting to tenth fractions of a per cent, and antimony and sulphur (about 1 wt % of each).

The principal lines in the debyeogram of breithauptite are as follows: 2.82(10); 2.06(10); 1.965(9); 1.616(5); 1.533(5); 1.248(5) and 1.080(6).

TABLE 42

Chemical composition of the minerals from the loellingite-safflorite-rammelsbergite series (wt %, X-ray micro-analysis)

Number of the analysis	Fe	Co	Ni	As	S	Sb	Total	Formula
1	27.0	-	-	71.6	0.4	-	99.0	$Fe_1(As_{1.08}S_{0.02})_2$
2	27.6	-	-	72.0	-	1.2	100.8	$Fe_1(As_{1.04}Sb_{0.02})_{1.08}$
3	26.2	0.7	-	69.0	-	3.3	99.2	$(Fe_{0.96}Co_{0.01})_1(As_{1.88}Sb_{0.06})_{1.94}$
4	17.2	0.6	10.0	69.8	0.3	2.0	99.9	$(Fe_{0.63}Ni_{0.35}Co_{0.02})_1(As_{1.91}Sb_{0.03}S_{0.02})_{1.96}$
5	17.0	7.1	4.0	68.0	2.2	2.8	101.1	$(Fe_{0.062}Co_{0.24}Ni_{0.14})_1(As_{1.84}S_{0.14}Sb_{0.05})_{2.03}$
6	13.9	7.0	8.7	60.2	6.6	2.0	98.4	$(Fe_{0.48}Ni_{0.29}Co_{0.23})_1(As_{1.55}S_{0.4}Sb_{0.03})_{1.98}$
7	12.0	4.6	12.5	62.0	4.0	5.8	100.9	$(Fe_{0.43}Co_{0.42}Ni_{0.15})_1(As_{1.64}S_{0.25}Sb_{0.1})_{1.99}$
8	11.0	12.2	9.0	53.0	10.0	4.0	99.2	$(Co_{0.37}Fe_{0.35}Ni_{0.28})_1(As_{1.28}S_{0.56}Sb_{0.06})_{1.90}$
9	8.6	7.2	12.0	62.0	4.0	5.8	100.9	$(Ni_{0.43}Fe_{0.32}Co_{0.25})_1(As_{1.71}S_{0.25}Sb_{0.1})_{2.06}$
10	0.3	12.5	17.5	69.2	0.6	-	100.1	
11	1.05	0.5	27.1	69.5	1.1	-	99.3	
12	14.45	3.65	8.8	71.5	0.4	-	99.8	
13	14.2	4.0	9.5	71.5	0.8	-	100.0	
14	14.1	4.35	9.68	71.3	0.4	-	99.63	
15	14.1	4.60	8.7	71.6	0.5	-	99.50	
16	14.1	4.65	9.65	69.6	0.7	-	99.0	

FOOTNOTE. 1-9---Noril'sk ore region; 10---Bu-Azzer*region, Morocco; 11-16---Malaga province, Spain.

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* Transliteration. Translator.

TABLE 43

Chemical composition of the zones with different Fe,Ni and Co ratios within a diarsenide grain (weight %, X-ray micro-analysis)

Zones	Fe	Ni	Co
A	27.8		
B	19.9	6.1	2.1
C	15.8	11.8	5.0
D	15.6	12.2	0.9

Ulmanite

Ulmanite occurs very rarely in association with breithauptite. It forms fringes around breithauptite or spotty and veinlet-like agglomerations with it.

Ulmanite has a constant chemical composition with trace elements represented by arsenic (2 to 4 wt %) and iron (tenth fractions of a per cent) (Table 41).

Native arsenic

Native arsenic had previously been unknown in deposits of copper-nickel ores. It was originally discovered in carbonate veinlets [57] cutting across massive pyrrhotite ores, in association with minerals of the loellingite-safflorite-rammelsbergite series, with which it forms zonal aggregates (Plate XIII,c).

Constant chemical composition; no trace elements have been detected.

The principal lines in the X-ray diffraction pattern of the arsenic are as follows: 3.54(3); 2.77(10); 2.05(7); 1.881(8); 1.767(4); 1.561(4) and 1.200(6). p.109

Native copper

Native copper has been very rarely encountered in ores. Native copper occurring in intergrowths with magnetite amidst sulphides, as well as other native metals and alloys (iron, awaruite, wairauite) have been described from the stratified intrusion at Muscox, Canada [188], where they formed in the process of serpentinization of ultrabasic rocks.

We detected homogeneous native copper only in the ores impregnated in picrite gabbro-dolerites, in interstitial and drop-like agglomerations of sulphides represented by the troilite-pentlandite-cubanite-mooihoekite (talnakhite) association. Copper is associated in these ores with late magnetite and mackinawite that form veinlets cutting across and replacing the sulphides mentioned earlier. It forms minutest crystals measuring 10μm or less, in the veinlets of magnetite and amidst mackinawite.

The identification of this mineral as native copper is supported by its high reflectance values, as well as by the data of the X-ray spectral micro-analysis, which detected only copper in its composition.

Perovskite

Perovskite forms well-shaped crystalline grains in veinlet-impregnated exocontact ores in association with pyrrhotite and chalcopyrite. Small perovskite crystals measuring 0.05-0.1mm occur at the boundary of sulphides with silicates of the country rock (Plate XIV,a), but have also been observed amidst the sulphides and in the nearby wallrock. The largest perovskite crystals are confined to the periphery of sulphide agglomerations. The small cribriform inclusions in the perovskite from the silicate country rock testify that the crystalline grains of perovskite are metacrysts. Replacement of pyrrhotite and chalcopyrite by later associations of pyrite, magnetite and valleriite, leaves the perovskite crystals intact.

Semiquantitative determinations of the composition of perovskite with the help of an electron-probe show that its principal components are calcium and titanium.

The principal lines of its X-ray diffraction pattern are: 2.71(10); 1.914(9); 1.572(5); 1.556(6); 1.357(4) and 1.031(4).

Pyrophanite

This rare mineral was discovered at the Noril'sk deposit in a pyrrhotite vein localized in picrite gabbro-dolerites. Pyrophanite occurs under highly specific conditions. It arises in the process of unmixing of the magnetite localized in the form of large grains up to 2mm in size along the selvage of the vein. Near the slender (up to 1.5mm) carbonate veinlets intersecting sulphide aggregates, this magnetite undergoes varying degrees of alteration and pyrophanite is one of its products of exsolution. It is represented by small (up to 0.08mm) grains that may associate with valleriite and non-metallic minerals. There have occasionally been observed complete pseudomorphs of these minerals in magnetite.

In reflected light pyrophanite is grey with a faint bluish tint. Anisotropic. Reflectance (R,%): 440 nm. - 19.2; 480 - 17.4; 520 - 16.0; 540 - 15.7; 580 - 15.3; 620 - 15.2; 660 - 14.8; 700 - 14.7; and 740 - 14.5.

The composition of pyrophanite: MnO-19.4; FeO-19.0; TiO_2-38.8; MgO-2.7; Cr_2O_3-7.7; Al_2O_3 - 0.6; V_2O_5-3.2; SiO_2-3.0; Σ-94.4 wt.%. In addition to MnO, it has unusually high contents of Cr_2O_3 and V_2O_5.

Principal lines of the debyeogram: 3.77(3)(110); 2.79(10)(211); 2.57(9)(101); 1.741(5)(321); and 1.518(3)(310).

Cassiterite

Cassiterite was discovered by N.N. Batyreva [1] in the course of detailed analyses of lumps of impregnated ores from gabbro-dolerites, and of massive and exocontact ores. Isolated grains of cassiterite were found in the heavy non-electromagnetic fraction of crushed samples. Cassiterite occurs in the form of spherical grains with a dull corroded surface or of angular, irregularly shaped fragments. There have occasionally been encountered grains with parts of crystal faces remaining intact. Cassiterite varies in colour from dark brown, nearly black, to light, almost colourless. Dark-coloured varieties predominate. There has often been p.110 observed zonal colouring. The mineral has been identified with the help of roentgenometric and laser microspectral analyses.

Cassiterite was found for the first time in copper-nickel ores in the USSR.J.Hawley [222] mentions a find of cassiterite in a sperrylite concentrate from the Sudbury ores.

MINERALS OF NOBLE METALS p.110

Minerals of gold, silver and platinum metals are typical accessories in the copper-nickel ores from Noril'sk. They are found in different association with one another and with the ore-forming sulphides and in varying quantities in all the types of ore. Gold-silver alloys are the most widely distributed minerals of gold and silver. A characteristic feature in the composition of these alloys is the presence of palladium, platinum, rhodium and copper. The other minerals, including hessite, a silver telluride, are found very rarely.

In contrast to the other copper-nickel deposits, at Noril'sk palladium minerals predominate in the ores and palladium or platinum compounds with tin, lead and bismuth are the most abundant minerals among them. They are followed in the order of diminishing abundance by Pt-Fe alloys, arsenides, Sn-arsenides and bismuth-tellurides of palladium or platinum, and by palladium and platinum sulphides.

The minerals of platinum metals found in the Noril'sk ores can be divided by composition into three main groups: 1) native Pt-metals and their alloys with one another or with Fe,Ni,Cu or Co; 2) intermetallides, i.e. compounds of Pt-metals with Pb,Bi,Sn,Te,As or Sb; and 3) sulphides, arsenides and sulpharsenides of Pt-metals. In each of these groups there have been observed isomorphous substitutions among the platinum metals. The other characteristic features observed in the second and third groups are a) the isomorphism of the metals* combined with platinoids (Bi,Sn,Pb,etc.), and b) the retention of the constant Σ platinoids: Σ partner-metal or Σ platinoids: S,Se,As (or S+As) ratios. In describing minerals of platinum metals we shall arrange them in the three groups specified above. Within each group the minerals will be examined in the order of decreasing contents of platinum metals: A_3B, A_2B, A_3B_2, etc. (where A is the platinum metal and B stands for Sn,Pb,Bi,Te,As,Sb,S or Se).

Minerals of gold, silver and platinum metals are closely associated in the ores and form polymineral intergrowths amidst sulphides or at the boundary of sulphides with magnetite or silicates. Monomineral agglomerations of these minerals are found less often.

Agglomerations of gold and silver minerals vary widely in morphology. They may be represented by xenomorphic inclusions in sulphides, by slender, often discontinuous veinlets within them, by fringes around the intergrowths of platinum minerals, by graphic intergrowths with these minerals, or by minutest inclusions in platinum minerals forming a pattern resembling colloidal dispersion.

Minerals of platinum metals have often been observed in the ores in the form of idiomorphic crystalline grains. Well-formed crystals are typical of sperrylite, cooperite, braggite, vysotskite, Pt-Fe alloys, rustenburgite, atokite, and paolovite. It should be emphasized that in addition to regular crystals, there have been encountered skeletal or immature crystals of most of these minerals, which permits us to classify them as metacrysts. Zonal crystals are highly distinctive.

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* "partner-metals" in Russian. Translator.

They are composed of a peripheral border of Pt-Fe alloy with atokite and stannopalladinite localized in the centre. Binary or polymineral intergrowths of platinum minerals are, however, the most wide-spread form of their agglomerations. Many platinum minerals occur in the form of veinlets or veinlet-like agglomerations amidst the ore-forming sulphides [19].

Minerals of noble metals vary in abundance in different mineral varieties of ores. They are more extensively developed in the ores in which minerals of the chalcopyrite group predominate. Their largest crystals have also been observed in these ores. The characteristic features of distribution of the minerals of platinum metals are the presence of cooperite, a platinum sulphide, in the ores impregnated in gabbro-dolerite intrusions and of cooperite, braggite and vysotskite in veinlet-impregnated and breccioid exocontact ores on the one hand, and the absence of these sulphides from massive ores, where intermetallides of platinum metals predominate, on the other. Impregnated ores from Noril'sk are similar in this respect to such ores from the Merensky Reef, South Africa, in which Pt-Fe alloys, cooperite and braggite predominate.

The shape of grains of the minerals of noble metals, their correlations with pyrrhotite, pentlandite, chalcopyrite group minerals and cubanite, and their close association with galena, sphalerite and, sometimes, djerfisherite show that most of these minerals evolved later than the principal ore-forming sulphides.

Native gold

Native gold is found in the ores less often than the other minerals of this group. In reflected light it is yellowish with a reddish tint, and isotropic. According to the data of L.V. Razin and V.D. Begizov [127], its composition is as follows (wt %): Au---68.9 - 79.5; Ag---17.3-23.2; Cu---0.1-0.9; Pd---1.4 - 2.9. According to our data, the content of palladium in native gold may be up to 3.5 wt %.

Electrum

Electrum is more common in the ores than native gold. Under the microscope its colour is gold-yellow without the reddish tint, and it is isotropic, similarly to native gold. Electrum commonly forms intergrowths with platinum minerals and often develops by replacing the peripheral parts of large porphyritic grains of pentlandite or arises from bornite (Plate XIV,b) in exocontact ores. In the composition of different grains of electrum there have been identified (wt %) Au---57.4 - 60.8, Ag---32.2-38.0, Pd---0.17 - 5.3, and Cu---0.04 - 0.15 (MS-46; I.P. Laputina, analyst). The data of L.V. Razin and V.D. Begizov [127] show even greater variations in the contents of constituent elements of this mineral (wt %): Au---48.4 - 59.7; Ag---23.2 - 50.9; Pd--- not found to 1.1; Cu---0.3 - 0.9.

Native silver

Native silver is most extensively distributed in talnakhite and mooihoekite ores, where it is represented by veinlets in sulphides (Plate XIV,c), as well as by intergrowths with platinum minerals, which it intensively replaces. Under the microscope the silver is bright white; at crossed nicols it is isotropic. It has been established that in addition to silver (96.8 - 98.6 wt %), this mineral contains up to 0.2% copper and 0.6% palladium [127]. According to our data, it also contains up to 4 wt % gold.

Küstelite

Küstelite is most widely distributed amidst gold-silver minerals. Küstelite is present in varying quantities in all the types of ores. In reflected light its colour is white with a faint yellowish tinge; optically isotropic; susceptible to light etching. It has been determined that the composition of küstelite is as follows (wt %): Ag-58.0 - 89.6; Au-9.6 - 44.0; Pd-not detected - 5.2; Cu- not detected - 0.5; Pt-not detected - 1.1; Rh-not detected - 1.9 [127].

Argentocuproarite

Argentocuproaurite is a solid solution of silver and copper in gold. It was originally discovered in concentrates of impregnated ores from the Noril'sk deposit in the form of small (10-30, rarely up to 80-100μm) agglomerations in association with gold, electrum and platinum minerals [126]. It has also been found at the Talnakh deposit [127]. Under the microscope argentocuproaurite is light pink with a reddish-orange tinge; isotropic. Its composition is as follows (wt %): Au-57.5 - 67.7; Ag-0.9 - 19.4; Cu-9.2 - 28.4; Pb-2.2 - 7.7; Pt-not detected - 3.8; Rh-not detected - 4.3 [126 and 127]. p.112

(Au, Pd)Cu*

Discovered in massive talnakhite ores from the Talnakh deposit. Occurs in intergrowths (0.1-0.2mm) with native silver, plumbopalladinite, majakite and zvyagintsevite [33]. Creamy-pink in reflected light. At crossed nicols weakly anisotropic, pleochroic in yellowish-brown and dark-blue tones. Reflectance (R,%): 440 nm. - 39.0; 460 - 39.4; 480 - 40.9; 500 - 42.8; 520 - 44.8; 540 - 46.8; 560 - 48.8; 580 - 50.4; 600 - 52.2; 620 - 54.4; 640 - 56.8; 660 - 59.6; 680 - 61.8; 700 - 64.0; 720 - 66.0; and 740 - 68.4.

Chemical composition of two grains: Au-69.6 and 67.5; Pd-4.7 and 7.0; Cu-25.2 and 26.0; Pt-0 and 1.0; Σ-99.5 and 101.5 (wt %). (MAR** 1; N.V. Troneva, analyst; Ms-46; Yu.E. Ugaste, analyst). Formulas: 1 - $(Au_{0.89}\ Pd_{0.11})_{1.0}Cu_{1.0}$ and 2 - $(Au_{0.84}Pd_{0.19}Pt_{0.01})_{1.04}Cu_{1.0}$.

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* Cuproauride, a compositionally similar mineral with the calculated formula $(Cu,Pd)_{3-x}Au_{2+x}$, was described by L.V. Razin et al. [125].

** Transliteration. Translator.

The X-ray diffraction pattern obtained is not of a very good quality (the mineral is malleable, ductile). Principal lines: 2.34(10); 2.23(3); 2.02(5); 1.431(3); and 1.220(5).

Stromeyerite

This mineral had never been encountered before in copper-nickel deposits. Found in association with millerite, polydymite, bornite, chalcopyrite and galena in veinlet-impregnated exocontact ores. Stromeyerite forms minutest (up to 10x20μm) crystals at the boundary of polydymite with bornite, chalcopyrite or millerite.

In reflected light the mineral is bluish-grey; it is susceptible to light etching, i.e. if stored for a long time, it changes in colour to bluish-green. Bireflectance perceptible; anisotropy distinct, in dark-blue tones. Magnitude of reflectance below that of bornite. Soft mineral, easily scratched during polishing.

It has been determined that the composition of stromeyerite is as follows (wt %): Ag - 55.0; Cu - 31.5; S - 15.8; Σ - 102.3, which corresponds to the formula $Ag_{1.03}Cu_{1.01}S$ (MS-46; I.P. Laputina, analyst).

Sulphosalt of silver, copper and lead

The mineral was found in brecciated chalcopyrite ores [85], where it forms slender (1-5μm in width) fusiform lamellas perpendicular to one another, in galena grains. The length to width correlation of the lamellas varies from 20:1 to 5:1.

Under the microscope, against the background of galena, this mineral displays a weak, but distinct bireflectance (greyish-white to dark greyish-greenish-blue). At crossed nicols it is distinctly anisotropic. Moderately high magnitude of reflectance, lower than that of galena.

It has been determined that the composition of this mineral is as follows (wt %): Ag - 24.06; Cu - 16.90; Pb - 10.1; Sb - 24.0; and S - 20.77 (MS-46; I.P. Laputina, analyst). Recalculation of the analysis gives us the formula $Ag_{8.94}Cu_{10.22}Pb_{1.95}Sb_{7.9}S_{26.0}$. Among the known sulphosalts there are no minerals with this kind of composition and proportions of constituent elements. Because of the extremely small measurements of its agglomerations (particles), we have been unable to analyze this mineral more thoroughly.

Hessite

Hessite occurs very rarely, mainly in copper-rich locales of massive or exocontact ores enriched in galena. Aggregates of hessite grains are associated for the most part with altaite, tellurian sobolevskite and other tellurobismuthides of platinum and palladium (Plate XIV,d), and form close intergrowths with them. Hessite aggregates may attain hundreds of μm in diameter.

In reflected light hessite has a grey-brown colour of a varying intensity (depending on the section) and a weak bireflectance. Its magnitude of reflectance is moderately high (R,%): 440 nm. - 39.5; 460 - 39.0; 480 - 38.2; 500- 38.0; 520 - 38.1; 540 - 38.3; 560 - 38.9; 580 - 39.5; 600 - 39.8; 620 - 40.0; 640 - 40.3; 660 - 40.9; 680 - 41.1; 700 - 41.2; 720 - 41.3; and 740 - 41.3. The crystal form characteristic of this mineral is very thin lamellar twinning that is perceptible at crossed nicols due to the strong anisotropy p.113 with pleochroic effects in predominantly reddish-brownish-greyish blue tones. Indentation hardness of hessite from the Oktyabr'skii deposit: 22kg/mm^2 (the mean of four measurements).

The composition of hessite from exocontact ores (JXA-50A; V.K. Garanin, analyst) is as follows (wt %): Ag - 62.09; Te - 37.38; Bi - 0.59; Σ - 100.06. The empirical formula of this mineral $Ag_{1.95}(Te_{0.99}Bi_{0.01})$ is close to its theoretical formula (Ag_2Te).

The principal lines of the X-ray diffraction pattern of hessite are 3.19(4); 2.99(6); 2.89(10); 2.31(5); 2.26(5); 2.14(4); and 1.394(3).

Natural alloys of platinum and iron

Platinum invariably contains iron and other elements of its group. In the literature distinction is made between native platinum, polyxene and ferroplatinum depending on the quantity of iron therein, but without defining in a clear-cut manner the limits of its contents or the structure of the alloys. The currently accepted nomenclature of natural Pt-Fe alloys is as follows [181]: 1) native platinum - disordered Pt-Fe alloys with a face-centered cubic unit cell; Pt content $\geqslant$ 80 at.%; 2) ferroan platinum - disordered Pt-Fe alloys with a face-centered cubic unit cell. A variety of native platinum with Fe contents ranging from 20 to 50 at.%. Varieties with high concentrations of Fe are distinguished by a high magnetic susceptibility. Platinum may be replaced by small amounts of Ir, Rh, etc., and iron by Cu, Ni, etc.; 3) isoferroplatinum - ordered Pt-Fe alloys with a cubic primitive unit cell, close in composition to Pt_3Fe; may contain small amounts of Ir, Rh, Cu or Ni; and 4) tetraferroplatinum - ordered Pt-Fe alloys with a tetragonal structure and a composition that is close to PtFe; may contain small quantities of Ir, Rh, Cu, Ni, etc.

Minerals of this group have so far been studied inadequately and at this time we can consider them as Pt-Fe alloys on the basis of their compositions.

Occurrence and associations. Pt-Fe alloy is one of the most widely distributed platinum minerals in the Noril'sk ores. In the ores impregnated in gabbro-dolerites of the Noril'sk deposit, it is represented by small platy cubic crystals (up to 0.2mm). In massive chalcopyrite and talnakhite ores from the Noril'sk and Talnakh deposits it forms veinlets amidst sulphides, borders around zvyagintsevite and stannopalladinite (Plate XV,a), and intergrowths with native silver and minerals of palladium, tin and arsenic.

Optical properties. The colour of individual grains is silver-white or steel-grey. Under the microscope, in reflected light it is bright white. At crossed nicols the mineral is isotropic. Reflectance varies slightly depending on the content of minor and trace elements. Reflectance (R,%) for Pt-Fe alloys (Fe+Ni$\cong$10wt.%) is as follows: 440nm. - 68.0; 460 - 67.7; 480 - 66.3; 500 - 65.8; 520 - 66.4; 540 - 67.1; 560 - 67.1; 580 - 67.4; 600 - 68.3; 620 - 69.2; 640 - 70.0; 600*** - 70.5; 620** - 71.0; 700 - 72.6; 720 - 73.6; and 740 - 74.4.

Chemical composition. In the samples from the Talnakh deposit the content of Pt varies from 77 to 88 wt %. The Fe content characteristic of these samples is up to 16 wt %. As the concentration of iron diminishes in the natural alloys, their copper and nickel contents rise (to a total of 6 wt %). Arsenic (up to 0.7 wt %) is found in them rarely (MAR*-1; N.V. Troneva, analyst).

X-ray data. The basic structural element of all the Pt-Fe alloys is a face-centered cubic unit cell (structural type Cu). V.I. Mikheev et al. [177] have demonstrated that the unit cell of the alloy decreases in size with increase in its iron content. In a later work [181] there have been constructed equations showing the parameters of the unit cell in ferroan platinum as a function of its Fe content (Fm3m).

As a result of X-ray studies there has been identified in chalcopyrite ores of the Noril'sk deposit tetraferroplatinum (a_0=3.84, C_0=3.78Å) [24] forming veinlets amidst chalcopyrite. There have also been obtained X-ray diffraction patterns evidencing the presence of isoferroplatinum in the ores. p.114

Solid solutions of tin and lead in palladium and platinum

As a result of the studies on synthetic Pd-Sn, Pd-Pb, Pt-Sn and Pt-Pb systems [151] it has been established that palladium and platinum may contain tin and lead in the form of solid solutions. The solubility thresholds determined for tin and lead are Sn - up to 17 at.% [234] and Pb - up to 14 at .% [257] in palladium and Sn - up to 8 wt % [4] in platinum.

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* Transliteration. Translator.

** Misprint for 680. M.F.

*** Misprint for 660. M.F.

There are few reliable data regarding the existence of this type of solid solutions in nature. Moreover, the phases described may be differentiated into two groups.

1. In native platinum from the Noril'sk ores there has been detected 8 wt % Sn [4]. A native palladium known from Colombia contains 8.1 wt % Pb [289];

2. A fairly detailed description of the natural phases referred to solid solutions of tin and lead in palladium and platinum, can be found in A.D. Genkin's work [20]. Many analyses of this type of "minerals" ($Pt_7Pd_{4.5}Sn_4$,$Pd_{11}Sn_{2.5}Pb_2$, etc.) are presented in the paper by L.V. Razin et al. [128].

Minerals of the second group are identical in properties and composition to Pt-atokite and Pd-rustenburgite. Their X-ray diffraction patterns display an assortment of lines characteristic of the cubic face-centered unit cell Fm3m, i.e. of the Cu-type structure. As is well known, for certain compositions there have been observed "order (space group Pm3m) - disorder (space group Fm3m)" inversions in structures of the Cu type, which explains the existence of partly ordered compounds close in composition to $(Pd,Pt)_3(Sn,Pb)$. Atokite and rustenburgite may be ordered to different degrees, which is reflected in the X-ray diffraction patterns in that lines with "mixed" indices ($\Sigma h+k+\ell=2n+1$) characteristic of the space group Pm3m, appear therein.

The data available at present thus testify that no "solid solutions of Sn and Pb in Pd and Pt" with large compositional fields exist in nature (or that no such solutions have been found). The minerals that do exist are a) native palladium and platinum containing a few per cent of Sn and Pb in addition to other minor or trace elements, and 2) compounds corresponding in composition and properties to Pt-atokite and

and Pd-rustenburgite with a general formula close to A_3B.

Minerals of the system Pd_3Sn - Pt_3Sn - Pd_3Pb - Pt_3Pb

The three minerals known from that system are atokite, rustenburgite and zvyagintsevite. The end members of atokite and rustenburgite Pd_3Sn and Pt_3Sn have not been as yet and we know only their platinian $(Pd,Pt)_3Sn$ and palladian $(Pt,Pd)_3Sn$ varieties. In reality tin minerals invariably contain small quantities of lead, and their formulas should be written as $(Pd,Pt)_3$ (Sn,Pb) and $(Pt,Pd)_3(Sn,Pb)$. Atokite and rustenburgite have very similar properties and can be distinguished only by their composition. This is due to the extensive isomorphism of Pd-Pt and Sn-Pb, as well as to the existence of the compositional field uniting atokites and rustenburgites. Zvyagintsevite, a Pd-Pb mineral, that was found initially [27], had significant contents of Sn and Pt,$(Pd,Pt)_3(Pb,Sn)$, but subsequently its end member Pd_3Pb was also identified.

Palladian rustenburgite-$(Pt,Pd)_3Sn$

Occurrence and associations. The mineral is named after the Rustenburg mine, Bushveld, South Africa [247], where it was discovered. Before that it was repeatedly recorded in the ores of the Talnakh and Oktyabr'skii deposits [33, 164 and 165]. This mineral occurs in massive cubanite-talnakhite and mooihoekite ores in the form of fairly large (up to 1mm) crystalline grains (Plate XV,b) or, sometimes, skeletal crystals. It forms intergrowths with plumbopalladinite, paolovite, polarite, sperrylite and $(Pd,Pt)_5(Sn,Sb)_2$.

Optical properties. In reflected light it is white and isotropic. Reflectance (R,%): 440 nm. - 60.3; 460 - 61.1; 480 - 62.5; 500 - 63.5; 520 - 64.3; 540 - 64.9; 560 - 65.9; 580 - 66.5; 600 - 66.3; 620 - 66.9; 640 - 68.4; 660 - 68.8; 680 - 68.6; 700 - 69.0; 720 - 68.9; and 740 - 69.2; p.115

Chemical composition. The contents of platinum and palladium in the mineral may vary markedly even within the same grain. Optical boundaries between grains have not been observed. Trace elements: copper, bismuth, antimony and nickel. Composition of two grains (MS - 46; I.D. Marchukova, analyst): Pt - 61.0 and 55.8; Pd - 15.7 and 23.1; Sn - 19.3 and 20.3; Cu - 1.4 and 1.2; Ni - 0.9 and 0.9; Σ - 98.3 and 101.3 (wt %). Formulas: $(Pt_{1.92}Pd_{0.91}Cu_{0.14}Ni_{0.09})_{3.06}Sn_{1.0}$ and $(Pt_{1.70}Pd_{1.27}Cu_{0.12}Ni_{0.08})_{3.17}Sn_{1.0}$.

X-ray data. According to the data in [245], rustenburgite has a cubic structure of the Cu type (space group Fm3m)*. All the X-ray diffraction patterns of $(Pt,Pd)_3Sn$ from the Noril'sk ores display lines with "mixed" indices pointing to the space group Pm3m, i.e. an ordered a_0 structure for $(Pt_{1.70}Pd_{1.27}Cu_{0.12}Ni_{0.08})_{3.17}Sn_{1.0} = 3.981$ Å. The principal lines of the debyeogram are 2.30(10)(111); 1.992(6)(200); 1.795(3)(210); 1.407(4)(220); and 1.197(3)(311).

Platinian atokite-$(Pd,Pt)_3Sn$

Occurrence and associations. The mineral has been named after the Atok mine, Bushveld, South Africa, where it was discovered [245]. It was detected previously in the Noril'sk ores [32,164, 165 and 128]. The mineral has been encountered at the Noril'sk deposit 1) in impregnated ores in the form of silver-grey crystals with a cubic habit (up to 0.7-0.9mm); and 2) in chalcopyrite veins, where it forms regular crystals (up to 0.8mm) and veinlets. At the Talnakh deposit atokite has been identified in massive chalcopyrite and cubanite-talnakhite ores in intergrowths with ferroplatinum, stannopalladinite, $Pd_5(Sn,As)_2$ and native silver (up to 0.3mm in size).

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* Ordering of the structure evident from the appearance of lines with "mixed" indices, is believed [245] to be induced by the stresses arising during the preparation of the sample.

Optical properties. White under the microscope. Isotropic. Reflectance (R,%): 440nm. - 61.3; 460 - 62.5; 480 - 64.1; 500 - 65.4; 520 - 66.4; 540 - 66.7; 560 - 66.8; 580 - 67.3; 600 - 67.6; 620 - 67.9; 640 - 68.6; 660 - 68.9; 680 - 69.5; 700 - 69.9; 720 - 70.3; and 740 - 70.6.

Chemical composition. The content of palladium in atokite is commonly three times its platinum content. Copper, lead, arsenic, antimony and bismuth may be present as trace elements totalling 10 wt % or less. For two different grains Pd - 47.0 and 38.0; Pt - 23.0 and 39.2; Au - 3.0 and 1.0; Ni - 0 and 0.4; Cu - 0 and 0.9; Ch* - 25.5 and 19.5; As - 0 and 0.9; Sb - 0 and 0.9; Σ - 98.5 and 100.8 wt % (MS-46, analyst- I.D. Marchukova, and MAR-1, analyst-N.V. Troneva, respectively). Formulas: $(Pd_{2.09}Pt_{0.55}Au_{0.07})_{2.71}Sn_{1.0}$ and $(Pd_{1.95}Pt_{1.10}Au_{0.03}Ni_{0.04}Cu_{0.08})_{3.20}(Sn_{0.90}As_{0.06}Sb_{0.04})_{1.0}$.

X-ray data. Virtually identical powder patterns for all the samples analysed. The assortment of lines is characteristic of the cubic structure of the Cu type (space group Fm3m). The primitive unit cell varies in size depending on the composition. For the grains examined $a_0 = 3.991$Å. The principal lines of the debyeogram are 2.30(10)(111); 1.992(7)(200); 1.411(5)(220); 1.201(4)(311); and 1.151(2)(222).

Zvyagintsevite-Pd_3Pb

Occurrence and associations. Zvyagintsevite was initially discovered at the Noril'sk deposit in pentlandite-chalcopyrite veins [27] where it was intergrown with ferroplatinum (Plate XV,c), and in talnakhite ores in association with polarite [176]. In massive ores from the Talnakh deposit zvyagintsevite forms borders around agglomerations of polarite [30] and (Au,Pd)Cu mineral in talnakhite.

* Presumably Sn, M.F.

Optical properties. White in reflected light; the tin-containing variety with a distinct creamy tinge. Isotropic. Reflectance (R,%): 440 - 58.6; 460 - 59.5; 480 - 59.9; 500 - 60.2; 520 - 62.1; 540 - 62.4; 560 - 62.9; 580 - 63.5; 600 - 63.5; 620 - 64.0; 640 - 64.6; 660 - 65.2; 680 - 65.7; 700 - 66.1; 720 - 66.5; and 740 - 66.6.

Chemical composition. Pd- 59.8; Pb - 40.1; Σ-99.9 (wt %). Formula: $Pd_{2.9}Pb$ (MAR-1; N.V. Troneva, analyst). There have been found varieties containing Au [176], Pt, Sn, Fe, Cu and Ni [27]. p.116

X-ray data. Structure of the type Cu_3Au. Space group Pm3m. a_o=4.018Å. Principal lines of the debyeogram: 2.33(10) (111); 2.01(8)(200); 1.422(6)(220); and 1.209(7)(311).

Paolovite and other minerals of the type Pd_2B(B = Sn,As,Sb).

In addition to the Pd_2Sn-paolovite [38 and 206], there have been encountered at the Noril'sk deposits several other minerals with formulas that may be written on the basis of Pd_2Sn: $Pd_2(Sn,Sb)$, $Pd_2(Sn,As)$ and $Pd_2(As,Sn)$. All these minerals are very rare and occur in close intergrowths with one another and with other MPM*, which makes it difficult to analyse them. Judging from the optic data, $Pd_2(Sn,Sb)$ is the closest mineral to paolovite. The $Pd_2(Sn,As)$ and $Pd_2(As,Sn)$ minerals are very similar to one another and may be of the same structural type Fe_2P.

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* Transliteration. "Minerals of palladium metals"? Translator.

Paolovite-Pd_2Sn

Occurrence and associations. Discovered initially in massive and impregnated troilite-pyrrhotite-chalcopyrite and cubanite ores from the Oktyabr'skii deposit. Paolovite forms 1) discrete idiomorphic grains (up to 100μm) that may be polysynthetically twinned (Plate XV,d), and 2) intergrowths (up to 200μm) with sperrylite, tellurian sobolevskite, $Pd_5Sn_2Cu_1$, niggliite, palladian rustenburgite and native silver, in which silver and paolovite commonly compose the peripheral region [33 and 38].

Optical properties. Lilac-pink in reflected light. Distinct bireflectance (lilac-pink to pale pink). At crossed nicols markedly anisotropic with bright pleochroic effect in orange-red and dark-blue tones (bright-red in immersion). Reversal of the optic sign has been observed. Reflectance (R'_g and R'_p,%): 440nm. - 44.0 and 43.2; 460 - 46.5 and 45.0; 480 - 48.0 and 46.3; 500 - 49.0 and 47.5; 520 - 51.1 and 49.2; 540 - 52.2 and 50.6; 560 - 53.5 and 52.2; 580 54.9 and 53.8; 600 - 56.3 and 56.7; 620 - 57.2 and 57.6; 640 - 58.3 and 59.9; 660 - 58.9 and 61.8; 680 - 59.8 and 63.7; 700 - 60.1 and 65.3; 720 - 60.2 and 66.2; and 740 - 60.2 and 66.9.

Chemical composition. Pd - 63.0; Sn - 37.0; Σ=100(wt %). May contain Pt (up to 3.0 wt %), Pb(0.3%), Bi(0.2%) and Sb(5.%) (MAR-1; N.V. Troneva, analyst).

X-ray data. Structure of the type δ-Ni_2Si. Space group Pbnm. a_o=8.11, b_o=5.65, and c_o=4.32Å. Principal lines of the X-ray diffraction pattern: 2.36(4)(310); 2.28(10)(121,301); 2.16(7)(002); 1.955(5)(112,320); 1.315(4)(610,731); 1.120(4)(612, 441,150,701); 1.078(5)(503,004).

$Pd_2(Sn,Sb)$

Occurrence and associations. This mineral has been encountered in massive troilite-pyrrhotite-chalcopyrite-cubanite ores from the Oktyabr'skii deposit in intergrowths with paolovite, sperrylite and sobolevskite (up to 50μm).

Optical properties. In reflected light it is very similar to paolovite. Bireflectance in more muted tones than that of Pd_2Sn. Anisotropic; pleochroic effects yellowish-brown to dark-grey.

Chemical composition. Pd - 64.2; Sn - 23.1; Sb - 13.0; Te - 0.1; Σ-100.0 (wt %). Formula: $Pd_{1.96}(Sn_{0.63}Sb_{0.37})_{1.0}$ (MS-46; I.D. Marchukova, analyst).

$Pd_2(Sn,As)$

Occurrence and associations. A very rare mineral. It occurs in pyrrhotite-chalcopyrite ores of the Oktyabr'skii deposit in association with Pd_5As_2 and $Pd_2(As,Sn)$ [33] and forms slender (up to 40μm) borders around Pd_5As_2.

Optic properties. Greyish-white under the microscope. No bireflectance observed. Anisotropic at crossed nicols. Pleochroic effects greyish-blue to violet-pink. Reflectance (R,%): 440nm. - 52.8; 460 - 52.5; 480 - 53.5; 500 - 53.1; 520 - 53.6; 540 - 53.9; 560 - 54.4; 580 - 55.5; 600 - 56.8; 620 - 57.5; 640 - 58.6; 660 - 59.2; 680 - 59.6; 700 - 60.2; 720 - 60.5; and 740 - 61.1. p.117

Chemical composition. The contents of Sn and As in the mineral vary somewhat. The composition of the mineral determined from two grains is as follows (wt %): Pd - 67.7; 67.7; Sn - 24.4; 27.5; As - 7.1; 5.1; Σ-99.2 and 100.3. Formulas: $Pd_{2.1}(Sn_{0.68}As_{0.32})$ and $Pd_{2.1}(Sn_{0.77}As_{0.23})$ (MS-46; Yu.E.Ugaste, analyst).

X-ray data. Very weak X-ray diffraction patterns. $Pd_2(Sn,As)$ may be referred to the structural type Fe_2P ($P\bar{6}2m$) with parameters of the primitive unit cell a=6.64Å and c=7.16Å. Practically the whole X-ray diffraction pattern can be identified in that unit cell.

Proceeding from the data on the chemical composition of the mineral, its formula can be written as Pd_6Sn_2As. This takes into account the following distribution of atoms in the primitive unit cell: 3Pd - 3(f)(1-x00); 3Pd - 3(g)(1-x0 1/2); 2Sn - 2(c)(1/3.2/3 0); 1As - 1(b)(00 1/2). Principal lines of the X-ray diffraction pattern: 2.42(10)$(11\bar{2}2)$; 2.25(9)$(20\bar{2}2)$; 1.906(3)$(30\bar{3}0)$; and 1.992$(23\bar{5}1)$.

$Pd_2(As,Sn)$

Occurrence and associations. A rare mineral. In massive pyrrhotite-chalcopyrite ores from the Oktyabr'skii deposit it forms slender (up to 40μm) borders around $Pd_2(Sn,As)$ in association with Pd_5As_2.

Optical properties. In reflected light greyish-white, similar to $Pd_2(Sn, As)$. At crossed nicols anisotropic; pleochroic effects bluish to orange-red. Reflectance (R,%): 440 nm. - 54.3; 460 - 53.4; 480 - 55.8; 500 - 55.4; 520 - 56.1; 540 - 55.9; 560 - 56.6; 580 - 57.5; 600 - 58.7; 620 - 59.3; 640 - 61.0; 660 - 61.2; 680 - 61.6; 700 - 62.1; 720 - 62.7; and 740 - 68.8.

Chemical composition. Pd - 70.2; Sn - 15.2; As - 15.5; Σ-100.9 wt%). (MS-46; I.D. Marchukova, analyst). Formula: $Pd_{1.96}(As_{0.62}Sn_{0.38})_{1.0}$.

X-ray data. Because of the small size of the grains, we have not succeeded in obtaining an X-ray diffraction pattern.

$(Pd, Pt)_5(Sn, As, Sb)_2$.

Occurrence, associations. Discovered at the Talnakh deposit in massive chalcopyrite and cubanite-talnakhite ores. Forms complex intergrowths measuring up to 1mm, with palladian rustenburgite, isoferroplatinum, sperrylite and polarite (Plate XVI,a) [33].

Optical properties. In reflected light it is creamy-white with a barely perceptible pale pink tinge. Weakly anisotropic at crossed nicols. Reflectance (R,%): 440nm. - 55.4; 460 - 57.0; 480 - 57.9; 500 - 59.0; 520 - 60.1; 540 - 60.9; 560 - 62.0; 580 - 62.5; 600 - 62.7; 620 - 63.5; 640 - 64.4; 660 - 65.2; 680 - 66.3; 700 - 67.4; 720 - 68.4; and 740 - 69.3.

Chemical composition. Pd - 67.5; Pt - 3.5; Au - 2.2; Cu - 0.7; Sn - 11.3; Pd[†] - 6.4; As - 5.6; Sb - 2.3; Bi - 2.1; Σ-101.0 (wt %). Formula: $(Pd_{4.55}Pt_{0.23}Au_{0.10}Cu_{0.05})_{4.93}(Sn_{0.97}As_{0.73}Pb_{0.19}Sb_{0.11})_{2.0}$ (MAR-1; N.V. Troneva, analyst).

The contents of all the elements vary somewhat (within the limits of 2-3 wt %), which does not, however, lead to significant deviations from the simplified formula $Pd_5(Sn, As)_2$. It may be possible to write the formula as Pd_5SnAs, since the stoichiometric proportions (Pd, Pt):(Sn, Pb, Bi):(As, Sb) =5:1:1 remain close for all the grains analysed.

X-ray data. Fairly simple X-ray diffraction pattern. Principal lines: 2.23(10); 1.805(4); 1.475(2); 1.240(2); 1.222(2); 1.152(2) and 1.060(2).

Stannopalladinite and other minerals of the Pd-Sn-Cu system

The distinguishing characteristic of these minerals is the presence of copper as an essential component. Stannopalladinite was initially described as a cuproan variety of the palladium-tin compound characterized by a constant Pd to Sn ratio (1.25 to 1.45) and by the presence of copper*. Later on [20] the formula of this mineral was written on the basis of microspectral data as Pd_3Sn_2 with a low content of copper (without indicating its p.118

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* According to the results of chemical analyses of seven platinum concentrate fractions [111].

[†] Misprint for Pb?, M.F.

position). O.E. Yushko-Zakharova et al. point out in their work [164] that the composition of stannopalladinite varies from $(Pd, Pt)_{2.3}Cu_{0.9}Sn$ to $(Pd, Pt)_{3.9}Cu_{0.9}Sn$. Somewhat later [165] stannopalladinite was examined once again with the formula $(Pd,Cu)_3Sn_2$. In the latest paper [175] the formula given for stannopalladinite is $(Pd, Cu)_3Sn_2$. In addition to the data pertaining to stannopalladinite, there appeared in the literature reports on a number of phases comprising Pd, Sn and Cu, but differing somewhat from one another, as well as from stannopalladinite, in the contents of these components and in properties: tetragonal $(Pd, Cu)_3Sn$ [165] that appears to be identical to the tetragonal modification $(Pd, Cu, Pt)_{3\pm x}Sn$ [128]; orthorhombic $(Pd, Cu, Pt)_{3\pm x}Sn$ [128 and 130]; taimyrite $(Pd, Cu, Pt, Ni)_{3\pm x}(Sn, Sb)$ [3] and other compounds.

At the present time it is difficult to give the definitive formula and characterization of stannopalladinite. The compositions of all the "minerals" described in the literature should be verified. Moreover, the analyses of all the phases should be carried out under identical conditions to preclude errors on account of using different makes of equipment or standards. It is equally imperative that we study the structure of these phases to determine the real position of copper in the crystal lattice. We describe here the three minerals analysed by us: stannopalladinite Pd_6CuSn_3, Pd_5Sn_2Cu and Pd_2SnCu, that are different mineral phases. Judging from the most recent data, copper occupies an independent structural position in these minerals. We have therefore chosen among the different variants the formula in which the three essential components (palladium, copper and tin) are treated separately.

Stannopalladinite

Occurrence and associations. Described originally from the Noril'sk deposit by I.N. Maslenitskii [11]*. Stannopalladinite occurs in the ore of chalcopyrite veins in the form of discrete spherical grains, agglomerations surrounded by fringes of ferroplatinum, or emulsion impregnation in ferroplatinum [20]. Regular crystalline grains with a zonal structure, in which stannopalladinite forms the central part (Plate XVI,b), occur at the Talnakh deposit in massive chalcopyrite and talnakhite ores. There have often been encountered intergrowths of stannopalladinite with plumbopalladinite, polarite and native silver surrounded by a borders of isoferroplatinum. Intergrowths of stannopalladinite with arsenides of palladium and nickel are less common.

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* The data presented in this work have been derived from a bulk analysis of several grains of the mineral. Minor quantities of other minerals may be present.

Optical properties. Light-pink in reflected light. Bireflectance in the air very weak with the colour changing from light-pink to light lilac-pink. At crossed nicols this mineral is anisotropic with bright pleochroic effects in orange-brown and dark-blue tones. Characteristic polysynthetic twinning; individual grains with a twin lattice texture. Reflectance (R,%) for two grains: 440nm. - 46.5 and 50.6; 460 - 47.9 and 51.0; 480 - 49.3 and 51.9; 500 - 50.9 and 53.2; 520 - 53.3 and 54.8; 540 - 54.6 and 55.9; 560 - 56.3 and 56.8; 580 - 57.5 and 57.7; 600 - 59.1 and 58.7; 620 - 60.0 and 59.4; 640 - 61.9 and 60.1; 660 - 63.8 and 60.7; 680 - 65.6 and 61.2; 700 - 67.3 and 62.0; 720 - 69.0 and 63.9; and 740 - 70.6 and 65.3. Compositional variations affect the shape and position of the reflectance spectrum.

Chemical composition. The distinguishing characteristic of the composition of stannopalladinite is the constant presence of copper in it (about 6 wt %). The contents of all the components vary markedly, but apparently independently of one another (with the exception of the direct correlation Pd-Pt). It is therefore rather difficult to calculate the formula of the mineral, since there are three possible variants of it: 1) Pd combined with Cu; 2) Cu combined with Sn; and 3) Pd, Sn and Cu in independent positions. Table 44 shows the compositions of two stannopalladinite grains and the formulas corresponding to the three above calculation variants.

X-ray data. X-ray diffraction patterns of stannopalladinite display a small assortment of lines, which may be due to the great ductility of this mineral. Its interplanar distances p.119 are fairly close to d_α of synthetic Pd_3Sn_2[257], which suggests that their formulas are also close: i.e. $Pd_3(Sn,Cu)_2$ or Pd_6Sn_2Cu rather than $(Pd, Cu)_3Sn$. Principal lines of the debyeogram: 2.30(10); 2.16(10); 2.01(3); 1.440(2) and 1.222(2).

TABLE 44

Chemical composition of stannopalladinite

N°N°	Contents (wt %) (MAR-1; N.V. Troneva, analyst)								
	Pd	Pt	Sn	Cu	Pb	Bi	Sb	As	Total
1	59.4	-	19.4	6.0	8.1	0.7	5.4	1.0	100.2
2	57.6	1.0	26.0	5.7	9.4	1.0	-	-	100.7

Formulas:

1 - $(Pd_{2.08}Cu_{0.35})_{2.43}(Sn_{0.61}Pb_{0.17}Sb_{0.16}As_{0.05}Bi_{0.01})_{1.0}Pd_{3.08}(Sn_{0.90}Cu_{0.52}Sb_{0.24}As_{0.08}Bi_{0.02})_{2.0}Pd_{6.16}Cu_{1.04}(Sn_{1.80}Sb_{0.48}Pb_{0.48}As_{0.16}Bi_{0.04})_{2.96}$.

2 - $(Pd_{2.01}Pt_{0.02}Cu_{0.33})_{2.36}(Sn_{0.81}Pb_{0.17}Bi_{0.02})_{1.0}(Pd_{3.02}Pt_{0.04})_{3.06}(Sn_{1.22}Cu_{0.50}Pb_{0.25}Bi_{0.03})_{2.0}(Pd_{6.04}Pt_{0.08})_{6.12}Cu_{1.0}(Sn_{2.44}Pb_{0.50}Bi_{0.06})_{3.0}$.

Pd_5Sn_2Cu*

Occurrence and associations. This mineral occurs in massive pentlandite-chalcopyrite ores of the Talnakh deposit in the form of borders (up to 40 µm) around paolovite.

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* Mentioned in A.D. Genkin et al.[33] as Pd_2 (Sn, Cu).

Optical properties. Pale-pink under the microscope. At crossed nicols it is anisotropic with weak pleochroic effects in orange-red and dark-blue tones. Reflectance (R,%): 440nm. - 57.2; 460 - 57.9; 480 - 60.0; 500 - 61.5; 520 - 62.1; 540 - 62.7; 560 - 63.5; 580 - 64.7; 600 - 65.5; 620 - 66.0; 640 - 66.4; 660 - 67.0; 680 - 67.9; 700 - 68.8; 720 - 70.0; and 740 - 71.3.

Chemical composition. Pd - 61.5; Pt - 3.5; Sn - 26.0; Cu - 7.5; Σ - 98.5 (wt %) (MS-46; Yu.E. Ugaste, analyst). Formula: $(Pd, Pt)_{4.92}Sn_{1.78}Cu_{1.0}$.

X-ray data. Very weak. X-ray diffraction pattern. Principal lines: 2.26(2); 2.15(10) and 1.438(1).

Pd_2SnCu*

Occurrence and associations. This mineral occurs at the Talnakh deposit [33] in exocontact ores amidst impregnated bornite in the form of discrete agglomerations or in intergrowths with sperrylite (Plate XVI,c). At the Oktyabr'skii deposit it forms discrete agglomerations 0.3-0.5mm in size in massive mooihoekite-cubanite and talnakhite-cubanite ores.

Optical properties. The mineral is commonly represented by aggregates of small grains with polysynthetic twins. Lilac-grey in reflected light; strong bireflectance; marked anisotropy with pleochroic effects in orange-red to greenish-blue tones. Reflectance (R'_g and R'_p,%): 440 nm. - 41.8 and 40.8; 460 - 42.5 and 41.2; 480 - 43.4 and 42.0; 500 - 44.2 and 42.2; 520 - 47.4 and 44.7; 540 - 48.7 and 44.7; 560 - 49.9 and 45.6; 580 - 52.1 and 46.8; 600 - 53.4 and 47.3; 620 - 55.5 and 48.9; 640 - 58.5 and 51.5; 660 - 61.0 and 53.6; 680 - 63.5 and 56.4; 700 - 65.8 and 58.4; 720 - 67.5 and 60.5; and 740 - 69.1 and 62.4.

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* This mineral may be analogous to taimyrite [3], but the authors provide no information other than the composition of this mineral.

Chemical composition. For two grains: Pd - 55.5 and 51.0; Pt - 0 and 1.0; Ag - 0 and 2.0; Sn - 27.5 and 30.0; Cu - 16.0 and 16.0; Sb - 2.2 and 1.0; Σ- 101.2 and 101.0 (wt %). (MS-46; analysts: I.D. Marchukova and Yu.E. Ugaste, respectively). Formulas:

1 - $Pd_{2.01}(Sn_{0.92}\ Sb_{0.08})_{1.0}Cu_{1.0}$
and
2 - $(Pd_{1.9}Pt_{0.02}Ag_{0.07})_{1.99}\ (Sn_{1.0}Sb_{0.03})_{1.03}Cu_{1.0}$

X-ray data. Principal lines of the X-ray diffraction pattern: 2.26(5); 2.17(10); 2.01(1); 1.929(6); and 1.815(2). p.120

Niggliite-PtSn

Occurrence and associations. Discovered originally at the Insizwa deposit and erroneously described at first as $PtTe_3$[270], thereupon as PtTe[210] and Pt_2Sn_3 [264]. The correct formula PtSn was determined by W.Uytenbogaardt [283]. Described in [162].

In massive pyrrhotite-chalcopyrite ores at the Talnakh deposit and in cubanite-chalcopyrite ores of the Oktyabr'skii deposit [87] niggliite forms minutest agglomerations (5-10μm) in paolovite and Pd-rustenburgite in association with sperrylite, froodite, native silver and galena.

Optic properties. Marked bireflectance in reflected light: pleochroic effect yellowish-pink to blue. At crossed nicols it is strongly anisotropic with bright pleochroic effects in bright orange (flame-coloured) to greyish-blue tones. Reflectance (R'_g and R'_p,%) 440 nm. - 51.0 and 43.0; 460 - 53.2 and 42.8; 480 - 55.5 and 42.6; 500 - 57.6 and 42.3; 520 - 59.4 and

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41.7; 540 - 60.7 and 41.0; 560 - 62.1 and 40.3; 580 - 63.6 and 39.6; 600 - 64.7 and 38.5; 620 - 65.4 and 36.4; 640 - 66.2 and 34.5; 660 - 67.1 and 32.5; 680 - 67.5 and 30.9; 700 - 68.0 and 30.2; 720 - 67.8 and 29.8; and 740 - 67.4 and 30.2.

Chemical composition. Pt - 59.5; Pd - 0.8; Cu - 0.08; Sn - 37.0; Te - 0.9; Σ - 98.28 (wt %). (MS-46; I.P. Laputina, analyst). Formula: $(Pt_{0.95}\ Pd_{0.03})_{0.98}(Sn_{0.98}Te_{0.02})_{1.0}$.

X-ray data. We have not succeeded in obtaining an X-ray diffraction pattern because of the small size of the grains.

Plumbopalladinite - Pd_3Pb_2

Occurrence and associations. Found originally in massive cubanite-talnakhite and talnakhite ores at the Talnakh deposit. Occurs in cubanite veinlets in the form of isolated agglomerations measuring up to 0.08mm, in association with galena and sphalerite, or in intergrowths with polarite (Plate XVI,d), stannopalladinite (Au,Pd)Cu, and native silver. The intergrowths may attain 0.5mm in size, but commonly measure 0.1-0.2mm [32].

Optic properties. In reflected light it is bright white with a barely perceptible pinkish tinge. Bireflectance perceptible in the air, more clearly pronounced in immersion. At crossed nicols this mineral is markedly anisotropic with pleochroic effects in orange-brown to dark-brown tones. Reflectance (R'_g and R'_p, %): 440nm. - 46.6 and 43.5; 460 - 48.2 and 44.6; 480 - 49.5 and 45.8; 500 - 50.8 and 47.5; 520 - 52.6 and 49.0; 540 - 54.4 and 50.7; 560 - 55.8 and 52.4; 580 - 57.1 and 53.9; 600 - 58.0 and 55.2; 620 - 59.2 and 56.6; 640 - 60.8 and 58.3; 660 - 62.6 and 60.0; 680 - 64.4 and 61.4; 700 - 66.1 and 62.8; 720 - 67.7 and 64.0; 740 - 68.7 and 64.8.

Chemical composition. For two grains: Pd - 41.6 and 42.0; Pb - 56.7 and 55.5; Bi - 0 and 1.1; Ag - 0 and 2.0; Sn - 0 and 0.5; Cu - 0.1 and 0.25; Sb - 0 and 0.1; Σ - 100.4 and 101.4 (wt %). (MAR-1, analyst- N.V. Troneva, and MS-46, analyst-I.P. Laputina, respectively).

Formulas: $Pd_{3.1}(Pb_{1.965}Bi_{0.035})_{2.0}$ and $(Pd_{2.8}Ag_{0.14})_{2.94}$ $(Pb_{1.900}Bi_{0.036}Sn_{0.029}Cu_{0.029}Sb_{0.006})_{2.0}$.

X-ray data. Structure of the type NiAs (partly filled). Parameters of the hexagonal primitive unit cell: a_0=4.470 and c_0=5.719 Å. The debyeograms of plumbopalladinite and synthetic Pd_3Pb_2 are identical. Principal lines: 3.20(5)(10$\bar{1}$1); 2.30(10)(10$\bar{1}$2); 2.23(10)(11$\bar{2}$0); 1.760(4)(11$\bar{2}$2); 1.602(4)(20$\bar{2}$2); 1.302(5)(21$\bar{3}$2); and 1.207(6)(11$\bar{2}$4).

Minerals of the system PdBi-PdTe-PdSb

There have now been discovered a number of palladium minerals that are very similar in physical properties and structure [68]. The composition of these minerals is characterized by a constant Pd:Te, Bi(Sb) (or Te+Bi) ratio. There has been identified a complete series of natural PdBi-PdTe compounds with the end members represented by sobolevskite (PdBi) and kotulskite (PdTe). Within that series there have been observed p.121 systematic variations in physical properties, i.e. in the reflectance (which increases as the content of tellurium rises) and elementary unit cell parameters (a and c of the hexagonal unit cell increase as the content of bismuth rises).

Sudburyite (PdSb), a mineral discovered by Canadian researchers [175], may also be referred to this group. It has the same structure (structural type NiAs), similar measurements of the primitive unit cell, and may contain minor quantities of Bi and Te.

Minerals of this group clearly exemplify the Bi-Te (and Sb) isomorphism.

Sobolevskite-PdBi.

Occurrence and associations. Sobolevskite was originally discovered in massive mooihoekite, chalcopyrite and troilite-cubanite ores at the Oktyabr'skii deposit [68]. It is represented by veinlet-like intergrowths with paolovite (Plate XVII,a) and sperrylite and by polymineral aggregates with galena, altaite, maslovite, michenerite, moncheite and froodite. In impregnated ores it forms intergrowths with moncheite and paolovite.

Optical properties. Under the microscope sobolevskite is greyish-white with a creamy tinge. It resembles kotulskite (PdTe). Distinct bireflectance in the air. At crossed nicols it is markedly anisotropic with bright pleochroic effects in reddish-lilac and light-creamy tones. Optically weakly biaxial, negative. Reflectance (R'_g and R'_p, %): 480nm. - 52.2 and 46.7; 500 - 53.6 and 48.3; 520 - 56.1 and 50.4; 540 - 57.7 and 52.4; 560 - 59.7 and 54.3; 580 - 61.0 and 55.5; 600 - 62.0 and 56.5; 620 - 63.5 and 57.8; 640 - 65.0 and 59.3; 660 - 66.2 and 60.2; 680 - 67.5 and 60.5; 700 - 68.3 and 60.8; 720 - 68.7 and 61.0; and 740 - 68.0 and 61.3.

Chemical composition. Essential components - Pd(34.4 wt %) and bismuth (66.2 wt %). There have occasionally been recorded in it minor quantities of platinum, lead, antimony and tellurium (MAR-1; N.V. Troneva, analyst).

X-ray data. X-ray diffraction pattern very close to the patterns of synthetic PdTe and kotulskite (structural type NiAs). Several weak lines have not been identified in the hexagonal unit cell with a_o=4.23 and c_o=5.69Å. Principal lines of the debyeogram: 3.07(10)$(10\bar{1}1)$; 2.26(10)$(10\bar{1}2)$; 2.11(9)$(11\bar{2}0)$; 1.74(4)$(20\bar{2}1)$; 1.690(5)(1013, $11\bar{2}2$); 1.342(4)$(10\bar{1}4)$; and 1.244(4) $(21\bar{3}2)$.

Kotulskite-PdTe

Occurrence and associations. Kotulskite was discovered originally at the Monchegorsk deposit [23], but is known from many other deposits: Rustenburg [233]; Stillwater [180] and Sudbury [184]. Kotulskite has been observed at the Talnakh and Oktyabr'skii deposits in millerite-chalcopyrite and bornite-millerite-chalcopyrite veinlet-impregnated and breccioid exo-contact ores [87] in intergrowths with telargpalite measuring 5 to 200 μm (Plate XVII,b), or in association with minerals of the PbS-PbTe system, vincentite, moncheite, braggite, cooperite, hessite, native gold and silver.

Optical properties. Creamy-white under the microscope. At crossed nicols it is anisotropic with pleochroic effects in greyish-blue to dark-brown tones. Reflectance (R,%): 440nm. - 50.9; 460 - 55.0; 480 - 57.3; 500 - 59.7; 520 - 61.7; 540 - 63.4; 560 - 64.7; 580 - 65.9; 600 - 67.2; 620 - 68.2; 640 - 69.1; 660 - 69.8; 680 - 70.5; 700 - 71.3; 720 - 71.3; and 740 - 71.8.

Chemical composition. The feature characteristic of kotulskite from the Oktyabr'skii deposit is the constant presence of lead (up to 3.1 wt %) and bismuth in it. For example, for two grains: Pd - 39.0 and 43.5; Pt - 0 and 0.02; Te - 26.1 and 52.6; Bi - 30.9 and 4.8; Pb - 2.8 and 1.5; Sb - 0 and 0.3; Σ - 92.8 and 102.9 (wt %). (MS-46; I.P. Laputina, analyst).

The respective formulas were calculated as

1 - $Pd_{1.0}(Te_{0.56}Bi_{0.40}Pb_{0.04})_{1.0}$

and

2 - $(Pd, Pt)_{0.92}(Te_{0.93}Bi_{0.05}Pb_{0.02})$.

X-ray data. Structure of the type NiAs. Synthetic PdTe has a_o=4.127 and c_o=5.663Å [209]. The parameter a_o of the hexagonal primitive unit cell increases as the content of bismuth in the mineral rises: at 17-20 wt % Bi [233] - a_o=4.145Å; at 24-26 wt % Bi [23] - a_o=4.19Å; and at 22-31 wt % Bi [87] a_o=4.188Å. Principal lines of the debyeogram: 3.04(10)$(10\bar{1}1)$; 2.23(10)$(10\bar{1}2)$; 2.08(9)$(11\bar{2}0)$; 1.723(4)$(20\bar{2}1)$; 1.674(5)$(10\bar{1}3)$; 1.528(6)$(20\bar{2}2)$; 1.332(5)$(10\bar{1}4)$; 1.233(6)$(21\bar{3}2)$; 1.175(8)$(11\bar{2}4)$; and 1.046(5)$(22\bar{4}0)$.

Polarite - Pd(Bi, Pb)

Occurrence and associations. Discovered originally by Canadian researchers [176] in a sample of ore from a lode at Noril'sk; described by A.D. Genkin et al.[30]. At the Noril'sk deposit polarite forms intergrowths with zvyagintsevite and Ni-Fe-platinum (up to 0.15mm) in talnakhite lode ores. In massive chalcopyrite, talnakhite and cubanite-talnakhite ores from the Talnakh deposit it forms intergrowths with zvyagintsevite, stannopalladinite (Plate XV,a), plumbopalladinite (Plate XVI,d), majakite, sphalerite and native silver.

Optical properties. In polished sections this mineral is white with a yellowish or greenish tint. At crossed nicols it is anisotropic with weak pleochroic effects (grey or pale-brown). Reflectance (R,%): 440nm. - 55.4; 460 - 56.8; 480 - 55.9; 500 - 56.4; 520 - 58.2; 540 - 59.2; 560 - 59.6; 580 - 59.6; 600 - 59.9; 620 - 59.5; 640 - 60.9; 660 - 61.2; 680 - 60.9; 700 - 61.8; 720 - 62.3; and 740 - 62.0.

Chemical composition. There have been observed significant variations in the relative contents of lead and bismuth at a practically constant content of palladium. Sb, Cu, Pt and Sn very rarely present as trace elements (attaining tenth fractions of a per cent). For two samples: Pd - 33.0 and 36.8; Pb - 49.5 and 16.0; Bi - 17.0 and 47.5; Σ - 99.5 and 100.3 wt %. Formulas: $Pd_{0.97}(Pb_{0.74}Bi_{0.26})$ and $Pd_{1.13}(Bi_{0.74}\cdot Pb_{0.26})$, respectively. (MS-46; Yu.E. Ugaste and I.D. Marchukova, analysts).

X-ray data. Debyeogram identical to that of synthetic PdBi. According to D.Kheikey et al. [152], the parameters of the orthorhombic (space group) $Ccm2_1$ unit cell are as follows: a_0=7.191; b_0=8.693 and c_0=10.68A. Principal lines of the debyeogram: 2.65(10)(004); 2.25(5)(331); 2.16(9)(124); 1.638(5)(144); 1.400(3)(062); and 1.169(3)(062,271).

The large range of the Pb - Bi and Bi - Pb isomorphous replacements and the similarity of the X-ray diffraction patterns

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for synthetic PdBi and PdPb suggest the existence of the almost complete series PdBi - PdPb. Isostructural end members PdBi and PdPb have not been found so far (the mineral PdBi known to us, i.e. sobolevskite, belongs to a different structural type), but should such minerals be found, they would probably have to be designated as "bismuthopolarite" and "plumbopolarite".

Bismutho-tellurides of platinum and palladium

Among the natural compounds of platinum, palladium, bismuth and tellurium of the type AB_2 ($A = Pt,Pd$; $B=Bi$, Te or $Bi+Te$) there have been distinguished three structural groups: 1) cubic minerals with the structure of the type of pyrite (or NiSbS)* - space group Pa3 (or $P2_13$): insizwaite ($PtBi_2$), michenerite (PdBiTe) and maslovite (PtBiTe); 2) hexagonal (or rather trigonal) minerals of the structural type $Cd(OH)_2$ - space group $P\bar{3}m1$: merenskyite ($PdTe_2$) and moncheite ($PtTe_2$); and 3) monoclinic froodite - space group C2/m. The position of all these mineral phases can be seen in the diagram of the quaternary system $PtBi_2$-$PdBi_2$ - $PdTe_2$ - $PtTe_2$ (fig. 23).

Compositions of the minerals belonging to the first group are arranged essentially within the triangular field $PtBi_2$ - PtTeBi - PdTeBi. The limits of the isomorphous replacement Pt → Pd and of bismuth by tellurium (but not of tellurium by bismuth) are probably fairly large [184 and 227]. It should be noted that another feature characteristic of michenerites and insizwaites is the presence in their compositions of traces of Sb (up to 5 wt %) and Ni (tenth fractions of a per cent). When the stoichiometry of the Bi:Te ratio (relative to 1:1) is disturbed, the degree to which the structure and symmetry of michenerite p.12
and maslovite are ordered, also changes: while PdTeBi and PtTeBi have a structure of the type NiSbS which is an ordered variant of the FeS_2 type of structure (pyrite), the structure characteristic of the tellurian varieties $Pd(Bi, Te)_2$ and $Pt(Bi, Te)_2$

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* Geversite ($PtSb_2$), another mineral with the structure of the type of pyrite, is very close to this group.

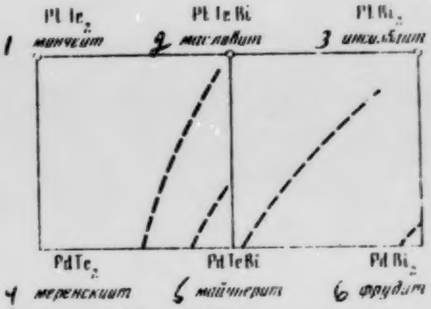
is highly symmetrical and disordered, of the type of pyrite.

TABLE 45

Measurements of primitive unit cells of palladium and platinum bismutho-tellurides.

Mineral	Formula	a_0	c_0	Literature
	Cubic			
Insizwaite	$(Pt_{0.90}Pd_{0.10})_{1.0}(Bi_{1.47}Te_{0.45}Sb_{0.09}Sn_{0.02})_{2.03}$	6.632		[184]
Michenerite	$Pd(Bi_{0.8}Sb_{0.21})_{1.01}Te$	6.642		[190]
	PdBiTe synthetic	6.651(5)		[179]
	$Pd_{1.00}(Te_{1.09}Bi_{0.91})_{2.00}$	6.654(5)		[227]
	$(Pd_{0.98}Pt_{0.02})(Te_{1.17}Bi_{0.86}Pb_{0.04}Sb_{0.02})_{2.09}$	6.665		Data of the authors
	$Pd_{0.95}(Bi_{1.11}Te_{0.94})_{2.05}$	6.651(5)		[227]
Maslovite	$(Pt_{0.53}Pd_{0.49})_{1.02}(Bi_{1.16}Te_{0.78}Sb_{0.05})_{1.99}$	6.671		[93]
	$(Pt_{0.71}Pd_{0.27})_{0.98}(Bi_{1.31}Te_{0.64}Sb_{0.07})_{2.02}$	6.689		[93]
	Hexagonal			
Merenskyite	$PdTe_2$	4.042(5)	5.124(8)	[227]
	$Pd(Te_{1.8}Bi_{0.2})$	4.040(4)	5.169(7)	[227]
	$Pd(Te_{1.7}Bi_{0.3})$	4.050(6)	5.186(6)	[227]
	$Pd(Te_{1.6}Bi_{0.4})$	4.045(3)	5.205(3)	[227]
	$Pd(Te_{1.5}Bi_{0.5})$	4.049(4)	5.231(4)	[227]
Moncheite	$(Pt_{0.9}Pd_{0.08}Ni_{0.02})_{1.0}(Te_{1.47}Bi_{0.52}Sb_{0.06})_{2.05}$	4.040(1)	5.297(6)	[184]

Fig. 23



Minerals of the system $PtBi_2$ - $PtTe_2$ - $PdTe_2$ - $PdBi_2$
1-Moncheite; 2-Maslovite; 3-Insizwaite; 4-Merenskyite;
5-Michenerite; 6-Froodite.

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The processes of replacement occur in bismuthotellurides of the hexagonal kind on a larger scale than in their cubic varieties [227], which may be due to a greater "isomorphous capacity" of the structural type $Cd(OH)_2$ than that of pyrite. Bismuth readily replaces tellurium in these minerals. In spite of the presumed existence of the complete series of solid solutions $(Pd,Pt)(Te,Bi)_2$ - $(Pt, Pd)(Te, Bi)_2$, it is difficult to draw at this time definitive conclusions regarding the limits of isomorphous replacements [233]. Practically all the moncheites and merenskyites described in the literature contain negligibly small quantities of palladium and platinum, respectively.

The size of the primitive unit cell of all the platinum and palladium bismuthotellurides is a function of their composition, as is also the case in the other minerals of a variable composition (Table 45). In hexagonal minerals the parameter $\underline{c}$ distinctly increases as the concentration of bismuth rises. In cubic minerals that correlation is more complex, but their parameter $\underline{a}$ also tends to increase as the content of bismuth rises.

The two groups of minerals are represented largely by their intermediate varieties at the Noril'sk and other deposits. These are tellurian and antimonian insizwaites, bismuthian michenerites, palladian-tellurian moncheites, etc. The problem of the nomenclature for the newly discovered minerals of that system can therefore be solved only after a detailed analysis of their composition. As concerns froodite, it is so far impossible to determine the limits of isomorphous replacements in the structure of that mineral because of the lack of experimental data and the fact that the only constituents identified in its composition in addition to palladium and bismuth, are small amounts of platinum and tellurium [36 and 184]. p.124

Insizwaite - $PtBi_2$

Occurrence and associations. Antimonian insizwaite was discovered originally at the Insizwa deposit, South Africa [175]. It occurs at the Oktyabr'skii deposit in the form of borders around cooperite, and sparse isolated grains (5-7μm) in a slender bornite-millerite-pentlandite-chalcopyrite vein. In massive pyrrhotite ores there have been encountered intergrowths of its Te-Sb varieties with altaite and palladium telluro-bismuthides (up to 30μm).

Optical properties. White with a bluish tinge and isotropic under the microscope. Reflectance for Te-Sb-insizwaite (R,%): 440 nm. - 56.0; 460 - 55.3; 480 - 54.7; 500 - 54.5; 520 - 54.2; 540 - 54.8; 560 - 55.0; 580 - 54.9; 600 - 54.8; 620 - 54.3; 640 - 54.1; 660 - 54.5; 680 - 54.8; 700 - 55.0; 720 - 54.4; and 740 - 54.0.

Chemical composition. Pt - 33.4; Bi - 66.9; Σ - 100.3 (wt %). Formula: $Pt_{1.07}Bi_2$. For the Te-Sb variety: Pt - 32.2; Pd - 1.9; Te - 11.2; Sb - 12.7; Pb - 1.1; Bi - 40.1; Σ - 99.3 (wt %), which corresponds to $(Pt_{0.9}Pd_{0.1})_{1.0}(Bi_{1.04}Sb_{0.57}Te_{0.48}Pb_{0.05})_{2.13}$ (MS-46; I.P. Laputina, analyst).

X-ray data. We have not succeeded in obtaining an X-ray diffraction pattern because of the small size of the grains.

Michenerite - PdTeBi

Occurrence and associations. Discovered at the Sudbury [224 and 179] and Monchegorsk [23] deposits. In impregnated ores from gabbro-dolerites of the Oktyabr'sk deposit [35 and 87] michenerite, intergrown with moncheite, forms veinlet-like agglomerations in chalcopyrite. In massive cubanite-chalcopyrite and mooihoekite ores there have been encountered polymineral intergrowths of michenerite with galena, altaite and sperrylite. Thin thread-like agglomerations of michenerite and merenskyite (Plate XVII,c) have been encountered in a veinlet-like body of pyrrhotite in pyrrhotite-chalcopyrite breccioid ores.

Optical properties. Greyish-white under the microscope. Isotropic. Reflectance (R,%): 440nm. - 57.8; 460 - 57.4; 480 - 57.0; 500 - 56.8; 520 - 56.4; 540 - 55.6; 560 - 55.7; 580 - 55.8; 600 - 59.9; 620 - 56.3; 640 - 56.6; 660 - 57.4; 680 - 58.3; 700 - 58.5; 720 - 58.9; and 740 - 59.4.

Chemical composition. The composition may vary with respect to minor components. Pd - 23.4; Pt - 0.75; Sb - 0.5; Te - 33.4; Pb - 1.9; Bi - 40.2; Σ - 100.05 (wt %). (MS-46; G.N. Muravitskaya, analyst). Formula: $(Pd_{0.98}Pt_{0.02})Te_{1.17}(Bi_{0.86}Pb_{0.04}Sb_{0.02})_{0.92}$.

X-ray data. Principal lines of the X-ray diffraction pattern: 2.98(10)(012); 2.76(6)(112); 2.01(5)(311); 1.781(3)(123); 1.455(3)(124); 1.178(4)(044); 1.080(3)(116).

Maslovite - $(Pt, Pd)Bi_{1+x}Te_{1-x}$

Occurrence and associations. Discovered in massive cubanite-chalcopyrite and mooihoekite ores from the Oktyabr'skii deposit in polymineral intergrowths with tellurian sobolevskite, moncheite, michenerite, altaite, hessite, minerals of the Pt-Pd-Cu-Sn-Sb system, froodite and sperrylite [93].

Optical properties. Light-grey with a lilac tinge under the microscope. Isotropic. Reflectance (R,%): 440 nm. - 55.9; 460 - 55.2; 480 - 55.0; 500 - 55.5; 520 - 56.0; 540 - 56.1; 560 - 55.9; 580 - 56.1; 600 - 56.3; 620 - 56.8; 640 - 57.1; 660 - 57.5; 680 - 58.4; 700 - 58.8; 720 - 59.2; and 740 - 59.4.

Chemical composition. A certain excess of Bi relative to the Bi:Te=1:1 ratio has been recorded in all the samples analysed. For two grains: Pt - 28.6 and 28.1; Pd - 4.5 and 5.0; Bi - 49.6

and 50.3; Te - 16.9 and 16.8; Sb - 0.8 and 0.8; Pb - 1.1 and 1.2; Σ - 101.5 and 102.0 (wt %). (MAR-2; V.D. Begizov, analyst). Formulas: 1 - $(Pt_{0.77}Pd_{0.22})_{0.99}(Bi_{1.25}Te_{0.70}Sb_{0.04}Pb_{0.03})_{2.01}$ and 2 - $(Pt_{0.75}Pd_{0.25})_{1.00}(Bi_{1.26}Te_{0.69}Sb_{0.02}Pb_{0.03})_{2.0}$.

X-ray data. The principal lines of the X-ray diffraction patterns for $(Pt_{0.71}Pd_{0.27})_{0.98}$ $(Bi_{1.31}Te_{0.64}Sb_{0.07})_{2.02}$ and $(Pt_{0.53}Pd_{0.49})_{1.02}(Bi_{1.16}Te_{0.78}Sb_{0.05})_{1.99}$, respectively, are 3.01 and 2.98(10)(012); 2.71(8)(412); 2.02 and 2.01(6)(311); 1.788(3) and 1.783(5)(123). Occasionally there has been p.125
observed a line with $d_\alpha = 2.10(310)$ testifying that this space group has a lower symmetry than Pa3.

Geversite - $PtSb_2$

Occurrence and associations. Discovered at Drickop occurrence, South Africa [276 and 280]. Found at the Noril'sk deposit in vertical chalcopyrite veins in the form of small (up to 120 μm) grains intergrown with stibiopalladinite or native gold [20].

Optical properties. Under the microscope light-grey and isotropic. Reflectance (R,%): 440nm. - 49.2; 460 - 50.6; 480 - 52.9; 500 - 54.9; 520 - 55.9; 540 - 56.9; 560 - 57.6; 580 - 58.7; 600 - 59.4; 620 - 60.1; 640 - 64.1; 660 - 61.8; 680 - 62.9; 700 - 62.8; 720 - 61.8; and 740 - 62.2.

Chemical composition. Pt - 47.5; Sb - 56.4; Σ - 103.9 (wt %). A minor quantity of Pd may be present (MS-46; I.P. Laputina, analyst). Formula $PtSb_{1.90}$.

X-ray data. $a_o = 6.44$ Å. Powder pattern coincides with that of synthetic $PtSb_2$. Principal lines: 3.23(4)(200); 2.88(7)(210); 2.63(4)(211); 2.28(4)(220); 1.944(10)(311); 1.719(4)(321); and 1.239(4)(333, 511).

Moncheite - $PtTe_2$

Occurrence and associations. Discovered at the Monchegorsk deposit [23]; identified at the Rustenburg mines, South Africa [233], and Sudbury [184]. At the Oktyabr'sk deposit [35 and 87] it has been detected in the ores impregnated in the rocks of the intrusion, where it is closely intergrown with michenerite and occurs amidst chalcopyrite. In massive troilite-pyrrhotite ores moncheite is found amidst troilite, cubanite and chalcopyrite in the form of minutest (5-10μm) agglomerations intergrown with froodite and paolovite. In breccioid millerite-chalcopyrite ores it forms intergrowths with kotulskite (40-70μm) amidst chalcopyrite.

Optical properties. Greyish-white in reflected light. Distinct bireflectance without changes in shades of colour. Markedly anisotropic at crossed nicols. Reflectance (R'_g and R'_p,%): 440nm. - 55.6 and 49.9; 460 - 55.7 and 50.5; 480 - 56.5 and 51.3; 500 - 57.3 and 52.0; 520 - 57.5 and 52.2; 540 - 57.6 and 52.5; 560 - 57.9 and 53.0; 580 - 58.2 and 53.3; 600 - 58.3 and 53.4; 620 - 58.2 and 53.4; 640 - 57.9 and 53.7; 660 - 58.0 and 54.1; 680 - 58.6 and 54.6; 700 - 58.5 and 54.9; 720 - 58.7 and 55.0; and 740 - 59.0 and 55.4.

Chemical composition. The most widely distributed variety of this mineral is bismuthian moncheite: Pt - 41.0; Te - 41.0; Bi - 19.0; Σ - 101.0 (wt %). (MS-46; I.D. Marchukova, analyst). Formula: $Pt_{1.02}(Te_{1.56}Bi_{0.44})_{2.0}$.

X-ray data. Principal lines of the debyeogram: 2.90(10)(10$\bar{1}$1); 2.10(9)(10$\bar{1}$2); 2.01(6)(11$\bar{2}$0); 1.654(5)(20$\bar{2}$1); 1.570(4)(10$\bar{1}$3); and 1.279(4)(12$\bar{3}$1).

Merenskyite - $PdTe_2$

Occurrence and associations. Described originally from the Rustenburg deposit, South Africa [233]; found at the Subbury deposit [267].

Occurs in pyrrhotite-chalcopyrite breccioid ores at the Oktyabr'skii deposit, where it is finely interpenetrated with michenerite [85]; agglomerations measuring up to 20-30μm.

Optical properties. Creamy-white and anisotropic under the microscope. Reflectance (R,%): 440nm. - 51.0; 460 - 52.7; 480 - 54.0; 500 - 55.2; 520 - 56.6; 540 - 57.7; 560 - 58.8;

580 - 59.2; 600 - 59.1; 620 - 58.6; 640 - 58.4; 660 - 58.2; 980* - 58.2; 700 - 58.1; 720 - 57.2; and 740 - 56.5.

Chemical composition. Pd - 27.8; Pt - 0.39; Sb - 0.29; Te - 58.2; Pb - 2.2; Bi - 15.7; Σ - 102.6 (wt,%). (MS-46; G.N. Muravitskaya, analyst). Formula: $(Pd_{0.99}Pt_{0.01})_{1.0}(Te_{1.73}Bi_{0.28}Pb_{0.04}Sb_{0.01})_{2.06}$.

A high percentage of nickel (5-17wt %) replacing isomorphously palladium has been determined in the merenskyite from Sudbury. This suggests that merenskyite may be regarded as a mineral forming a solid solution with melonite $NiTe_2$ [267].

X-ray data. We have not succeeded in obtaining an X-ray diffraction pattern because of the small size of agglomerations of this mineral.

Froodite - $PdBi_2$

Occurrence and associations. Discovered in the Frood mine at the Sudbury deposit [224, 179 and 184]. Described in [161] with the formula $PdB_{2.7}$. In massive pentlandite-pyrrhotite p.126 -chalcopyrite ores of the Oktyabr'skii deposit froodite forms borders around sperrylite and $Pd_2(Sn,Sb)$ in a close association with altaite [36]. In cubanite-talnakhite, talnakhite and pyrrhotite ores it forms very small agglomerations (up to 50μm) amidst intergrowths of sobolevskite, sperrylite, Pd_2 (Sn,Sb) and native silver.

Optical properties. Under the microscope it is greyish-white with a perceptible greenish tinge. Weakly anisotropic at crossed nicols. Reflectance (R,%): 440nm. - 56.0; 460 - 57.3; 480 - 58.4; 500 - 59.8; 520 - 61.0; 540 - 62.8; 560 - 63.7; 580 - 64.3; 600 - 64.0; 620 - 63.6; 640 - 63.8; 660 - 63.9; 680 - 63.9; 700 - 63.6; 720 - 63.0; and 740 - 61.8.

Chemical composition. Pd - 18.8; Pt - 0.95; Cu - 0.07; Bi - 79.7; Σ - 99.5 (wt %). (MS-46; G.N. Muravitskaya, analyst). Formula: $(Pd, Pt, Cu)_{0.97}Bi_2$.

* misprint for 680, M.F.

X-ray data. Unit cell parameters in froodite: a_o=12.75; b_o=4.29; c_o=5.67Å, β=102°53'. Principal lines of the debyeogram: 2.97(10)(310); 2.81(5)(311); 2.76(9)(002, 202); 2.21(9)($\bar{3}$12, 112); 2.14(5)(510, $\bar{5}$11, 020); 2.09(3)($\bar{6}$01); 1.687(3)(022, $\bar{2}$22, 313); and 1.552(3)($\bar{6}$03, $\bar{7}$12, 512, 800).

Urvantsevite - $Pd(Bi,Pb)_2$*

Occurrence and associations. Discovered originally by N.S. Rudashevskii et al. [131] in massive pentlandite-cubanite-chalcopyrite ores of the Talnakh deposit, where it occurs in intergrowths with $(Pd,Pt,Cu)_3Sn$, PdBi, Pd_2Sn, native silver, froodite, altaite and galena. Grains irregularly spherical in shape, measuring 0.01-0.04mm. We identified urvantsevite in massive talnakhite-cubanite ores from the Oktyabr'skii deposit in intergrowths with paolovite containing a certain amount of antimony.

Optical properties. In reflected light the mineral is greyish-white with a very low relief. At crossed nicols it is weakly anisotropic; reflectance [131] (R'_g and R'_p %, respectively): 440nm. - 48.7 and 50.5; 460 - 53.2 and 54.9; 480 - 54.6 and 53.8; 500 - 54.1 and 53.3; 520 - 54.8 and 53.7; 540 - 55.2 and 54.0; 560 - 56.2 and 54.9; 580 - 56.7 and 55.2; 600 - 57.6 and 56.1; 620 - 58.3 and 56.8; 640 - 59.2 and 57.8; 660 - 60.1 and 58.6; 680 - 60.9 and 59.6; and 700 - 61.3 and 59.6.

Chemical composition of urvantsevite is fairly constant and is close to the empirical formula Pd_2PbBi_3 [131]. Mean contents: Pd - 20.5; Bi - 64.6; Pb - 15.3 (wt %). For urvantsevite from the Oktyabr'skii deposit: Pd - 18.2; Pt - 1.1; (Pb - 16.7;) Bi - 63.9; Cu - 0.2; As - 1.2; Σ - 101.3 wt %, which corresponds to the formula $(Pd_{0.95}Pt_{0.03}Cu_{0.02})_{1.0}(Bi_{1.70}\,Pb_{0.45}As_{0.09})_{2.24}$. (MS-46; I.P. Laputina, analyst).

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* O.E. Yushko-Zakharova and L.A. Chernyaeva analyse in their work [163] the mineral Pd_3Pb_3Bi that is close in optical properties to urvantsevite; 2) may be identical to "plumbofroodite" of V.D. Begizov and S.F. Sluzhenikin [3].

X-ray data. Debyeogram of urvantsevite is identified in the hexagonal unit cell with a=13.82 and c=6.53Å. Principal lines: 2.643(10)$(21\bar{3}2)$; 2.372(8)$(22\bar{4}2)$; 2.043(5)$(51\bar{6}1)$; 1.685(5)$(43\bar{7}2)$; 1.420(7)$(71\bar{8}2)$; 1.335(5)$(72\bar{9}2)$; 1.166(6)$(55\overline{10}3)$*; and 1.111(7)$(92\overline{11}2)$*.

Arsenides of palladium and nickel

This group of minerals comprises for the most part extremely rare and poorly studied compounds with distinctive optic properties and X-ray characteristics. The correlation of Pd and Ni in these minerals is not entirely clear at this time. It is obvious that in some of the minerals of palladium metals (michenerite, moncheite, sudburyite, etc. [175])containing small quantities of Ni, nickel isomorphously replaces palladium and that they are combined in the formula [e.g. (Pd,Ni)(Sb, Bi, Te, As) - sudburyite]. This is readily understandable, since the Pd and Ni atoms are fairly close in properties and size. In the Pd and Ni group of arsenides the situation is more complex. The contents of nickel are fairly high in these minerals and their Pd:Ni ratios are often stoichiometric (mineral $Ni_6Pd_2As_3$). This suggests that Ni may have an independent position in the structures of these phases. Preliminary calculations of the variants of the majakite (PdNiAs) structure take into account the ordered or disordered distribution of Pd and Ni in the unit cell. p.127 These calculations have corroborated that the arrangement of the metal atoms is ordered. Proceeding from this, palladium and nickel are separated in the variants of formulas selected for majakite and $Ni_6Pd_2As_3$, and occupy independent positions. As concerns $(Pd, Ni)_5As_2$, we have unfortunately no adequate material at this time that would permit us to verify either of the two variants, and we proceed entirely from the similarity of its properties and X-ray diffraction patterns to those of Pd_5As_2, which brings us to the formula $(Pd, Ni)_5As_2$.

* ? M.F.

The data available in the literature are highly incomplete and pertain only to a few of the minerals from this group: 1) $Pd_3Ni_4As_3$ [163]; 2) $(Pd, Ni)_{2+x}As$; $(Ni, Pd)_{2+x}As$; $(Ni, Pd)_{5+x}As_2$ [128]; 3) $(Pd, Ni)_2(As, Te)$ or PdNi(As, Te) [182].

The last compound of those listed above appears to be analogous in composition and optic properties to majakite. It is difficult to compare the other compounds with those described by us.

Pd_5As_2

Occurrence and associations. Very rare in the Noril'sk ores [33]. In massive pyrrhotite-chalcopyrite ores from the Oktyabr'skii deposit Pd_5As_2 grains are confined to veinlet-like agglomerations of pyrrhotite in chalcopyrite. It associates with $(Pd, Ni)_5As_2$ and $Pd_2(Sn, As)$ (Plate XVII,d). Intergrowths of these minerals measure up to 0.4mm.

Optical properties. Greyish-white in reflected light. Bireflectance weak with the colour changing to light-pink. Anisotropic at crossed nicols. Reflectance (R,%): 440 nm. - 52.7; 460 - 54.3; 480 - 55.6; 500 - 57.1; 520 - 58.4; 540 - 59.5; 560 - 59.9; 580 - 60.3; 600 - 61.5; 620 - 62.0; 640 - 62.8; 660 - 63.0; 680 - 66.6; 700 - 64.2; 720 - 64.4; and 740 - 65.2.

Chemical composition. Pd - 76.0; Ag - 3.0; As - 21.0; Sb - 1.5; Σ - 101.5 (wt %). (MS-46; Yu.E. Ugaste, analyst). Formula: $(Pd, Ag)_{5.07}\cdot(As, Sb)_{2.0}$.

X-ray data. The mineral is finely intergrown with $(Pd, Ni)_5As_2$ and $Pd_2(Sn, As)$, which makes it difficult to analyse it. In spite of the great similarity between this mineral and synthetic Pd_5As_2, there are some differences in their X-ray diffraction patterns. In the literature there is information regarding another phase of a similar composition, the "unnamed Pd_5As_2" [182]. The X-ray diffraction pattern of that mineral is very similar to the pattern obtained by us. The differences between them pertain to the intensity of the lines and may be due to different conditions of photography.

Parameters of the orthorhombic primitive unit cell of the "unnamed Pd_5As_2": a=11.216; b=3.875; and c=11.345Å [182]. Principal lines of the X-ray diffraction pattern: 2.78(3)(212); 2.61(10)(311); 2.54(5)(402); 2.45(8)(203); 2.27(10)(410, 403); 2.21(6)(313, 501); 1.982(10)(015); 1.803(10)(221, 122); and 1.755(6)(315).

$(Pd, Ni)_5As_2$

Occurrence and associations. In massive pyrrhotite-chalcopyrite ores from the Oktyabr'skii deposit this mineral forms lamellar agglomerations (platy crystals) and fringes (up to 90μm) in Pd_5As_2 in association with $Pd_2(Sn, As)$ (Plate XVIII, d).

Optical properties. Greyish-white in reflected light. Bireflectance weak with the colour changing from greyish-white to light-blue. Anisotropic at crossed nicols. Reflectance (R, %): 440 nm. - 54.6; 460 - 55.3; 480 - 55.3; 500 - 55.9; 520 - 57.5; 540 - 58.1; 560 - 59.2; 580 - 59.2; 600 - 60.6; 620 - 61.8; 640 - 62.8; 660 - 63.5; 680 - 63.6; 700 - 6.4*; 720 - 64.6; and 740 - 65.3.

Chemical composition. Pd - 57.0; Ni - 15.5; Ag - 3.0; As - 23.0; Sb - 1.5; Σ - 100.0 (wt %). (MS-46; Yu.E. Ugaste, analyst). Formula: $(Pd_{3.3}Ni_{1.65}Ag_{0.2})_{5.15}(As_{1.92}Sb_{0.08})_{2.0}$.

X-ray data. X-ray diffraction pattern very similar to that of Pd_5As_2. The two minerals appear to be of the same structural type. Principal lines of the debyeogram: 2.77(3); 2.44(8); 2.27(10); 2.19(10); 2.11(4); 1.989(6); 1.808(10); and 1.753(6).

Palladoarsenide - Pd_2As

Occurrence and associations. Discovered originally at the Talnakh deposit [2] in veinlet-impregnated pentlandite-chalcopyrite exocontact ores in the form of veinlet-like intergrowths with Pd_5As_2 measuring 5 to 400μm; found at Stillwater, USA [182].

* misprint for 64.4? M.F.

p.128

Optical properties. In reflected light greyish-white with a pink tinge (in immersion the pink tint is brighter and bireflectance is perceptible). At crossed nicols it is moderately anisotropic with pleochroic effects from dark-grey to reddish-brown. Characteristic patchy-mosaic structure of the grains. Reflectance (R,%) [2]: 400 nm. - 39.0; 430 - 45.7; 460 - 47.6; 490 - 49.1; 520 - 50.8; 550 - 51.8; 580 - 52.6; 610 - 54.2; 640 - 55.4; 670 - 57.1; and 700 - 59.0.

Chemical composition. Pd - 67.0; Ag - 3.4; Au - 1.2; As - 2.61*; Σ - 98.0 (wt %) (MS-46; Yu.E. Ugaste, analyst). Formula: $(Pd_{1.83}Ag_{0.09}Au_{0.02})_{1.94}As_{1.0}$.

X-ray data. The powder pattern of palladoarsenide is identical to that of the low-temperature modification Pd_2As [268]: space group P2/m; a_0=9.25±0.01; b_0=8.47±0.02; c_0 10.44±0.02Å, β =94.0°, d_{x-ray}=10.42 g/cm^3 at Z=18. Principal lines of the debyeogram: 2.60(7)(004, 131); 2.35(6)(114, $\bar{2}31$); 2.31(6)(400); 2.21(9)(024, 401); 2.14(10)($\bar{1}33$, 313); 2.13(5)(214, 124); 2.12(5)(040); 1.955(7)($\bar{3}32$, 042); 1.576(5)($\bar{2}51$, $\bar{3}15$); and 1.093(4)($\bar{2}48$, $\bar{1}74$).

Majakite - PdNiAs

Occurrence and associations. Found originally in massive chalcopyrite and talnakhite ores at the Talnakh deposit in intergrowths with polarite (Plate XVII,e), Pd-Sn-Cu---minerals and plumbopalladinite. Agglomerations measuring a few microns to 0.1mm [39].

In massive troilite-pyrrhotite-cubanite-chalcopyrite ores of the Oktyabr'skii deposit it forms small (up to 50μm) intergrowths with PdBi and native gold in pentlandite.

Optical properties. Greyish-white in reflected light. No bireflectance observed either in the air or in immersion. Weakly anisotropic at crossed nicols (no pleochroism observed). Reflectance (R,%): 440nm. - 47.4; 460 - 49.0; 480 - 50.5; 500 - 51.2; 520 - 52.3; 540 - 52.8; 560 - 54.4; 580 - 55.2; 600 - 55.8; 620 - 56.1; 640 - 56.7; 660 - 58.0; 680 - 57.9; 700 - 58.5; 720 - 59.0; and 740 - 59.2.

* misprint for 26.4? M.F.

Chemical composition. Pd - 44.3; Ni - 25.2; As - 32.0; Σ= 101.7 wt % (MS-46; I.P. Laputina, analyst). Formula: $Pd_{0.98}Ni_{1.01}As_{1.0}$.

X-ray data. Structural type Fe_2P, possibly with an ordered arrangement of Pd and Ni. Space group P62m, a_o=6.066 and c_o=7.20Å. $d_{X\text{-}ray}$=10.6 g/cm^3; d_{synth} PdNiAs=9.33 g/cm^3; Z=6. Principal lines of the X-ray diffraction pattern: 3.04(4)$(11\bar{2}0)$; 2.65(10)$(20\bar{2}0)$; 2.40(4)(0003); 2.30(5)$(11\bar{2}2)$; 2.19(7)$(10\bar{1}3)$; 1.988(10)$(12\bar{3}0)$; and 1.800(4)(0004).

$Ni_6Pd_2As_3$

Occurrence and associations. Discovered in massive cubanite-talnakhite ores of the Talnakh deposit in intergrowths with majakite amidst stannopalladinite. $Ni_6Pd_2As_2$* agglomerations measuring ~ 0.1mm.

Optical properties. In reflected light greyish-white with a scarcely perceptible bluish tinge. Weakly anisotropic at crossed nicols. Reflectance (R_g' and R_p', %): 440 nm. - 49.3 and 47.2; 460 - 49.3 and 47.3; 480 - 49.3 and 46.8; 500 - 49.7 and 47.4; 520 - 50.1 and 48.0; 540 - 50.8 and 48.5; 560 - 51.0 and 48.8; 580 - 51.6 and 49.5; 600 - 52.7 and 50.5; 620 - 53.7 and 51.5; 640 - 54.8 and 52.5; 660 - 55.9 and 53.5; 680 - 56.7 and 54.0; 700 - 58.0 and 55.5; 720 - 59.3 and 56.5; and 740 - 60.4 and 57.0.

Chemical composition. Pd - 26.0; Ni - 44.6; As - 28.0; Σ=98.6 (wt %). (MS-46; I.P. Laputina, analyst). Formula: $Ni_{6.12}Pd_{1.95}As_{3.0}$. Another possible variant in the case of isomorphism of Ni-Pd is $(Ni, Pd)_{8.07}As_{3.0}$.

X-ray data. We have only succeeded in obtaining a very weak film. Principal lines of the X-ray diffraction pattern: 2.28(3); 2.20(4); 2.02(10) and 1.931(3).

Minerals of the system Pd - As - Sb - [Te]

This group amalgamates natural compounds of a complex composition: arsenopalladinite Pd_8 (As, Sb)$_3$ [191 and 185]; stibiopalladinite (Pd, Cu)$_{5+x}$ (Sb, As, Sn)$_{2-x}$ [129 and 183];

* Misprint for $Ni_6Pd_2As_3$?

merticeites I and II - $(Pd, Cu)_{5+x}(Sb,As)_{2+x}$ or $Pd_8(Sb, As)_3$ [199 and 182]; isomertieite $(Pd, Cu)_5(Sb, As)_2$ (stoichiometry has not been established with precision, possibly $\Sigma(Pd+Cu):\Sigma(Sb+As)=8:3$ or 11:4) [191, 182 and 175]; stillwaterite $Pd_8(As, Sb, Te, Sn, Bi)_3$ [182 and 185]; vincentite $(Pd, Pt)_3(As, Sb, Te)$ [278]; and unnamed mineral phases 1) $Pd_5(Sb, As)_2$ [191] and 2) Pd_8Sb_3 [182]. p.128

The features characteristic of all the above minerals are that they commonly comprise 3-6 components, the ambiguity in the determination of their formulas and stoichiometry, and their distinctive crystal structures. Because of these features the group described is one of the most difficult groups to analyse*.

Stibiopalladinite - $Pd_{5+x}Sb_{2-x}$

Occurrence and associations. Discovered originally at Potgietersrust, South Africa [288 and 183]. Identified at the Noril'sk deposit [20] in the locales of vertical chalcopyrite veins adjoining the selvages, where it occurs in association with geversite, cooperite, sperrylite and native gold. Platy grains of stibiopalladinite measure about 0.1mm. In breccioid chalcopyrite ores of the Oktyabr'skii deposit it forms small isolated platy crystals up to 0.1mm in size.

Optical properties. Under the microscope white with a pale-pink tinge. Anisotropic with distinct pleochroic effects in reddish and greyish-blue tones. Reflectance (R,%): 440nm. - 43.6; 460 - 46.4; 480 - 47.9; 500 - 49.5; 520 - 51.2; 540 - 52.7; 560 - 54.1; 580 - 55.3; 600 - 55.7; 620 - 56.1; 640 - 57.4; 660 - 58.0; 680 - 58.7; 700 - 59.5; 720 - 60.3; and 740 - 60.8.

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* The arsenoantimonides and arsenostannides of palladium described by L.V. Razin and L.S. Dubakina [129] from the Oktyabr'skii deposit, undoubtedly also belong to this group. Unfortunately the data on the chemical composition and X-ray diffraction patterns presented by these authors are highly contradictory and make it impossible to identify these minerals with complete confidence.

Chemical composition. Pd - 69.7; Pt - 0.81; Sb - 29.7; Cu - 0.11; Σ - 100.3 (wt %). (MS-46; G.N. Muravitskaya, analyst). Formula $(Pd, Pt)_{5.4}\ Sb_2$ or $(Pd,Pt)_{8.01}Sb_3$.

X-ray data. The parameters of the hexagonal primitive unit cell for synthetic Pd_5Sb_2 are a_o=7.603 and c_o=13.853Å [183]. For the sample from the Oktyabr'skii deposit they are a_o=7.577 and c_o=27.79Å. Principal lines of the X-ray diffraction pattern: 3.38(1)$(11\bar{2}4)$; 3.15(1)$(01\bar{1}8)$; 2.50(3)$(12\bar{2}1)$; 2.30(10)$(02\bar{2}9)$; 2.198(10)$(03\bar{3}0)$; 2.03(7)$(12\bar{2}8)$; 1.943(2)$(12\bar{2}9)$; 1.870(2)$(03\bar{3}8)$; 1.584(4)$(22\bar{4}10)$*; 1.492(2)$(23\bar{5}2)$; 1.427(2)$(14\bar{5}2)$; 1.352(2)$(23\bar{5}9)$; 1.283(2)$(14\bar{5}10)$;* 00022)*; and 1.333(4)$(05\bar{5}8;\ 14\bar{5}12)$*.

Mertieite II - $(Pd, Pt)_8(Sb, As)_3$

Occurrence and associations. Discovered at Goodnews Bay, Alaska, USA [199 and 182] and at Sudbury [184]. In veinlet-impregnated exocontact ores of the Oktyabr'skii deposit it is represented by xenomorphic grains in association with galena, moncheite, tellurian sobolevskite, hessite, hauchecornite and parkerite [92].

Optical properties. Creamy-yellow in reflected light. Bireflectance perceptible (without changes in colour). Reflectance (R'_g and R'_p, %): 440nm. - 47.0 and 44.0; 460 - 49.3 and 47.0; 480 - 51.2 and 49.1; 500 - 53.4 and 50.8; 520 - 54.5 and 51.7; 540 - 55.8 and 53.4; 560 - 56.9 and 54.2; 580 - 58.0 and 54.7; 600 - 59.3 and 55.4; 620 - 60.4 and 55.6; 640 - 61.4 and 56.0; 660 - 62.3 and 56.4; 680 - 62.9 and 56.5; 700 - 64.4 and 57.3; 720 - 65.3 and 57.7; and 740 - 66.3 and 57.8.

Chemical composition. For two grains: Pd - 69.3 and 68.9; Cu - 2.3 and 2.3; Sb - 28.0 and 28.0; As - 2.2 and 2.2; Σ - 101.8 and 101.4 (wt %). Formulas: 1 - $(Pd_{7.57}Cu_{0.42})_{7.99}\ (Sb_{2.67}As_{0.34})_{3.01}$ and 2 - $(Pd_{7.55}Cu_{0.47})_{8.02}\ (Sb_{2.68}As_{0.34})_{3.03}$ (MAR-2; V.D. Begizov, analyst).

X-ray data. Powder pattern identical to that of mertieite II [182]. Parameters of the hexagonal unit cell: a_o=7.60 ± 0.01 and c_o=43.00±0.1Å. Principal lines: 3.13(5)$(02\bar{2}4)$;

* ? M.F.

2.48(3)$(21\bar{3}1)$; 2.28(9)$(11\bar{2}, 15)$; 2.25(2)$(20\bar{2}.14)$; 2.19(10)$(30\bar{3}0)$; 1.582(5)$(22\bar{4}.15)$; 1.282(2)$(14\bar{5}.15)$; and 1.228(2)$(41\bar{5}.18)$. p.130

Vincentite - $Pd_3(As, Te)$[*]

Occurrence and associations. Described from platinum-bearing placers of the island of Borneo [278]. Identified at the Oktyabr'skii deposit [87] in bornite-millerite-chalcopyrite exocontact ores in the form of grains intergrown with kotulskite and telargpalite and measuring 30 μm.

Optical properties. Pinkish-brown in reflected light. Weakly anisotropic. Reflectance (R,%): 440nm. - 44.1; 460 - 44.9; 480 - 46.3; 500 - 47.5; 520 - 49.4; 540 - 51.5; 560 - 53.1; 580 - 54.7; 600 - 56.0; 620 - 57.5; 640 - 58.8; 660 - 60.4; 680 - 61.6; 700 - 62.9; 720 - 63.1; and 740 - 64.3.

Chemical composition. Pd - 76.2; As - 11.0; Te - 10.5; Pb - 1.5; Bi - 0.6; Σ - 99.8 (wt %). Formula: $Pd_{3.00}(As_{0.615}Te_{0.343}Pb_{0.029}Bi_{0.013})_{1.0}$ (MS-46; I.P. Laputina, analyst).

X-ray data. We have not succeeded in obtaining an X-ray diffraction pattern because of the small size of the grains.

$Pd_5(Sb, As)_2$

Occurrence and associations. Discovered at the Itabira mine, Brazil [191]. In the contact zone of massive ores at the Oktyabr'skii deposit it forms small intergrowths with sperrylite measuring up to 40 μm.

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[*] E.F. Stumpfl and M. Tarkian [278] described a mineral with the composition $(Pd,Pt)_3(As,Sb,Te)$: grain I - $(Pd_{2.66}Pt_{0.34})_{3.00}(As_{0.45}Te_{0.32}Sb_{0.24})_{1.00}$ and grain II - $(Pd_{2.58}Pt_{0.41})_{2.99}(As_{0.44}Sb_{0.35}Te_{0.22})_{1.00}$.

Optical properties. Pale-creamy in reflected light. Weakly anisotropic at crossed nicols (without pleochroic effects).

Chemical composition. Pd - 73.1; Sb - 16.2; As - 11.4; Cu - 0.5; Σ - 101.2 (wt %). Formula: $(Pd_{7.30}Cu_{0.08})_{7.38}(As_{1.60}Sb_{1.40})_{3.0}$ (MS-46; I.P. Laputina, analyst). This mineral is close in composition to isomertieite - $(Pd, Cu)_5(Sb, As)_2$ [191] or $(Pd, Cu)_8(Sb,As)_3$ [182].

X-ray data. Because of the minute size of the grains it was impossible to obtain an X-ray diffraction pattern.

Telargpalite - $(Pd, Ag, Bi, Pb)_{4+x}Te$

Occurrence and associations. Discovered originally in veinlet-impregnated exocontact bornite-millerite-chalcopyrite ores at the Oktyabr'skii deposit in intergrowths with clausthalite, kotulskite (Plate XVII,b), vincentite and $(Pd,Ag)_3(Ag, Pb)(Te,Se)$ [87 and 88]. Polymineral aggregates measuring ~0.01 x 0.08mm.

Optical properties. In reflected light telargpalite is light-grey with a barely perceptible lilac tinge. Isotropic. Reflectance (R,%): 440nm. - 44.7; 460 - 45.3; 480 - 46.6; 500 - 47.5; 520 - 49.1; 540 - 50.1; 560 - 50.9; 580 - 51.7; 600 - 52.4; 620 - 53.7; 640 - 54.6; 660 - 55.6; 680 - 56.7; 700 - 57.2; 720 - 57.4; and 740 - 58.4.

Chemical composition. Content of Te more or less constant; variable lead and bismuth concentrations. For two grains: Pd - 39.3 and 38.9; Ag - 29.5 and 30.5; Te - 20.2 and 20.1; Se - 0.1 and 0; Pb - 3.8 and 8.5; Bi - 5.9 and 2.1; Σ - 98.7 and 101.1 (wt %). Corresponding formulas: 1 - $(Pd_{2.34}Ag_{1.69}Pb_{0.13}Bi_{0.17})_{4.33}(Te, Se)_{1.00}$ and 2 - $(Pd_{2.30}Ag_{1.80}Pb_{0.26}Bi_{0.09})_{4.40}Te_{1.00}$ (MS-46; I.P. Laputina, analyst).

V.A. Kovalenker et al. [88] also examine in their work other variants of calculated formulas for telargpalite.

X-ray data. Structure unknown. By analogy with the cubic Pd_4Te phase [208] the parameter a_o of the cubic unit cell of telargpalite is 12.60Å. Principal lines of the debyeogram: 3.05(4)(410); 2.42(10)(333); 2.10(5)(600); 1.822(2)(444); and 1.475(3)(661).

(Pd, Pt)(Pb, Bi)(S, Se)

Occurrence and associations. Found in bornite-millerite-chalcopyrite veinlet-impregnated exocontact ores from the Oktyabr'skii deposit in the form of isolated spherical or elongated grains (measuring 25-30μm) in chalcopyrite in association with telargpalite, $(Pd, Ag)_3(Ag,Pb)(Te,Se)$, kotulskite and p.131
clausthalite [85].

Optical properties. Under the microscope it is pale-blue with a lilac tint. At crossed nicols anisotropic with pleochroic effects from greyish-blue to brownish-red. Reflectance (R,%): 440nm. - 42.4; 460 - 43.7; 480 - 44.7; 500 - 45.1; 520 - 44.9; 540 - 42.2; 560 - 45.1; 580 - 44.8; 600 - 44.8; 620 - 45.4; 640 - 45.7; 660 - 46.3; 680 - 46.5; 700 - 46.9; 720 - 47.0; and 740 - 47.2.

Chemical composition. There have been established significant variations in the contents of lead and bismuth, palladium and platinum, sulphur and selenium; as the concentration of one of the components in each pair increases, the content of the other component declines. For one of the grains: Pd - 32.4; Pt - 0.4; Pb - 47.7; Bi - 4.6; S - 7.8; Se - 4.7; Σ - 97.6 (wt %). Formula: $(Pd_{1.01}Pt_{0.01})_{1.02}(Pb_{0.76}Bi_{0.07})_{0.83}(S_{0.8}Se_{0.2})_{1.0}$ (MS-46; I.P. Laputina, analyst).

X-ray data. We have not succeeded in obtaining an X-ray diffraction pattern.

$(Pd, Ag)_3(Ag, Pb)(Te, Se)$

Occurrence and associations. Discovered in veinlet-impregnated exocontact bornite-millerite-chalcopyrite ores at the Oktyabr'skii deposit. Forms small (10-50μm) spherical intergrowths with kotulskite, telargpalite and braggite in association with clausthalite and (Pd,Pt) (Pb,Bi)(S, Se) [87].

Optical properties. Under the microscope it displays a distinctly observable bireflectance with the colour changing from bluish-grey to pinkish-lilac. At crossed nicols it is markedly anisotropic with pleochroism from greenish-yellow to burning-orange. Reflectance (R'_g and R'_p, %): 440nm. - 39.9 and 37.5; 460 - 42.3 and 38.2; 480 - 43.6 and 39.6; 500 - 44.2 and 40.6; 520 - 44.4 and 41.1; 540 - 44.7 and 42.4; 560 - 44.5 and 43.3; 580 - 44.7 and 44.4; 600 - 45.0 and 45.2; 620 - 44.9 and 46.1; 640 - 45.2 and 46.8; 660 - 45.0 and 46.5; 680 - 45.4 and 46.5; 700 - 45.1 and 46.3; 720 - 44.7 and 45.7; and 740 - 44.2 and 44.9.

Chemical composition. Pd - 38.7; Ag - 25.5; Pb - 13.7; Bi - 0.8; Te - 16.8; Se - 3.7; Σ - 99.2 (wt %). (MS-46; I.P. Laputina, analyst). Formula: $(Pd_{2.17}Ag_{0.83})_{3.0}(Ag_{0.58}Pb_{0.40}Bi_{0.02})_{1.0}(Te_{0.79}Se_{0.28})_{1.07}$.

X-ray data. We have not succeeded in obtaining an X-ray diffraction pattern.

Sulphides of platinum and palladium

This group comprises three minerals: cooperite, braggite and vysotskite. They commonly form idiomorphic crystals, less often intergrowths. Cooperites are close in composition to PtS, with 4-5 wt % or less Pd and Ni. Braggite is characterized by a wide compositional field with variable contents of Pt, Pd and Ni. In the triangular diagram PtS - PdS - NiS (fig. 24) the compositions of braggite form a fairly extensive series in which the Pd:Ni$\sim$2:1 ratio persists, while the Pt: Σ Pd+Ni ratio is variable. This agrees with the results obtained from structural analyses of the mineral [190] and is due to the distribution of the Pt, Pd and Ni atoms between the structural positions in the tetragonal unit cell with the space group $P4_2/m$; Pt and Ni are statistically located at the 2c and 4f, while Pd occupies the 2d position. The formula of braggite determined on the basis of the structural analysis is $(Pt, Ni)_{6-x}Pd_{2+x}S_8$.

For vysotskite there is noted the presence of a small amount of Pt and the constant ratio of Pd and Ni = 3:1. By analogy with braggite, referred to the same structural type, one can assume that in the tetragonal cell of vysotskite (space group $P4_2/m$) the atoms of Pd and Ni occupy independent structural positions. Therefore two variants are possible; (1) Pd 2e, 4f, Ni 2d; and (2) Pd-2d and 4f, Ni-2e. Such a formula for vysotskite can be given as $Pd_6Ni_2S_8$.

Cooperite - PtS

Occurrence and associations. Discovered originally at the Bushveld deposit [194, 167 and 171]. At the Noril'sk deposit small crystals of cooperite have been encountered in veins and insets of pyrrhotite ores. In breccioid millerite-chalcopyrite ores larger (0.3-0.5mm) idiomorphic crystals p.132 of this mineral have been observed amidst chalcopyrite, sometimes in association with sphalerite and vysotskite [20]. In bornite-pentlandite-millerite and chalcopyrite-millerite exocontact ores from the Talnakh deposit it forms small (up to 150μm) crystals and intergrowths with braggite. In pyrrhotite, pyrrhotite-chalcopyrite and chalcopyrite breccioid ores (at the Oktyabr'skii deposit) there occur small, well-formed cooperite crystals with perfect facets (30-180μm), or, sometimes, very fine-grained aggregates composed of minutest grains of cooperite and native platinum.

Optical properties. Cooperite crystals steel-grey in colour. Under the microscope they are greyish-blue. At crossed nicols it is distinctly anisotropic with pleochroic effects from light-grey to greyish-blue. Reflectance (R,%): 440nm. - 44.0; 460 - 44.1; 480 - 43.6; 500 - 42.9; 520 - 41.9; 540 - 41.3; 560 - 40.5; 580 - 40.1; 600 - 39.5; 620 - 38.8; 640 - 38.2; 660 - 37.6; 680 - 37.0; 700 - 36.4; 720 - 35.7; and 740 - 35.2.

Chemical composition. Principal components - Pt and S (Table 46). Invariably contains a certain amount of Pd. A feature characteristic of cooperites from the Noril'sk deposit is the presence of nickel in it (up to 1.2 wt %).

X-ray data. Space group $P4_2/mmc$, $a_0=3.46$ and $c_0=6.10$Å. Principal lines of the debyeogram: 3.01(10)($0\underset{\smile}{\overset{\frown}{\ }}02$, 012); 2.465(3)(110); 1.918(7)(112); 1.512(6)($0\underset{\smile}{\overset{\frown}{\ }}22$, 121); 1.240(3)(123); 1.157(2)(015); 1.139(3)(222, $0\underset{\smile}{\overset{\frown}{\ }}31$); and 1.034(4)(132).

Braggite - (Pt, Pd, Ni)S

Occurrence and associations. Found originally in deposits of the Merensky Reef [171]. At the Talnakh deposit isolated grains and intergrowths of braggite with cooperite, vysotskite and tellurides of palladium, silver, lead and bismuth (up to 0.2-1mm) have been encountered in veinlet-impregnated bornite-millerite-chalcopyrite ores.

Optical properties. Greyish-white under the microscope. Weakly anisotropic at crossed nicols. Reflectance (R,%): 440nm. - 45.2; 460 - 44.5; 480 - 45.0; 500 - 45.7; 520 - 46.3; 540 - 47.2; 560 - 48.1; 580 - 48.5; 600 - 48.3; 620 - 48.3; 640 - 48.9; 660 - 48.3; 680 - 47.9; 700 - 48.1; 720 - 47.8; and 740 - 48.0.

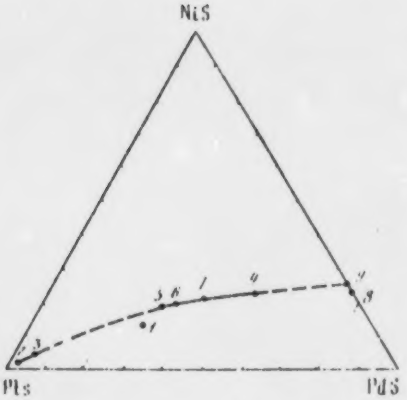
Chemical composition. The composition of this mineral (see Table 46) varies widely with regard to the Pt/Pd(0.44-2.0) and Pt/Ni(1.14-4.4) ratios [105].

X-ray properties. Structure of the PdS type. Space group $P4_2/m$; $a_0=6.38$ and $c_0=6.59$Å. Principal lines of the X-ray diffraction pattern: 3.17(1)(200); 2.92(6)(102); 2.85(10)(210); 2.63(7)(211); 2.14(1)(212); 1.857(5)(222); 1.805(2)(203); 1.771(2)(302); 1.712(3)(312); 1.592(1)(400); 1.541(1)(410); 1.422(3)(214, 420); 1.397(3)(412); 1.380(1) (523); and 1.036(3)(610).

Vysotskite - (Pd, Ni)S

Occurrence and associations. Discovered originally at the Noril'sk deposit [22, 33 and 164] in breccioid and impregnated chalcopyrite-millerite ores in the form of small prismatic or irregularly shaped crystals (Plate X, a) in nickeloan pyrite, polydymite or violarite.

Fig. 24



Composition of platinum and palladium sulphides [105]
1-Braggite from South Africa; 2-Cooperite from South Africa [171]; 3-Cooperite from the Talnakh deposit; 4-7---Braggites from the Talnakh deposit; 8 and 9 - From the Talnakh deposit.

Optical properties. In reflected light greyish-white with a bluish-lilac tint. Bireflectance (greyish-bluish to greyish-lilac) observable only in immersion. Anisotropic; pleochroic effects in brownish or dark-blue tones. Reflectance (R,%): p.133
440nm. - 49.2; 460 - 49.5; 480 - 51.1; 500 - 51.6; 520 - 51.8; 540 - 52.3; 560 - 52.5; 580 - 52.6; 600 - 52.6; 620 - 53.1; 640 - 53.2; 660 - 53.6; 690-53.8; 700 - 54.0; 720 - 54.0; and 740 - 54.0.

The chemical composition is characterized by a practically constant Pd/Ni 3:1 ratio (Table 46).

X-ray data. Powder pattern close to the debyeogram of braggite. Structure of the PdS type. Parameters of the tetragonal unit cell: a_0 =6.37 and c_0 =6.55Å. Principal lines of the debyeogram: 3.74(4)(111); 3.16(5)(200); 2.91(10)(102); 2.86(10)(210); 2.64(7)(112); 2.61(8)(211); 2.22(6)(212); 1.859(7)(222); 1.732(6)(213); 1.717(8)(312); 1.636(5)(004); 1.419(6)(214); 1.396(6)(412); 1.185(8)(502); 1.138(7)(404); 1.121(6)(414); 1.071(6)(106); and 1.031(9)(611).

TABLE 46

Chemical composition of braggite, cooperite and vysotskite (wt %, X-ray micro-analysis)

N°N°	Pt	Pd	Ni	Cu	Fe	Ag	S	Total
1	86.4	-	0.64	-	-	-	13.7	100.7
2	83.1	0.9	1.2	-	-	-	13.5	98.7
3	80.3	2.5	1.5	-	-	0.4	15.0	99.7
4	56.0	19.5	6.0	-	-	-	18.5	100.3
5	31.5	38.5	8.3	0.3	-	0.2	21.5	100.3
6*	0.3	63.1	10.6	0.7	-	-	25.2	99.9
7*	0.4	62.5	11.6	1	0.3	-	25.4	100.2

FOOTNOTE. 1-3---Cooperite: 1-$(Pt_{1.03}Ni_{0.02})_{1.05}S$ (MS-46; G.N. Muravitskaya, analyst); 2-$(Pt_{1.00}Ni_{0.04}\ Pd_{0.02})_{1.06}S$ (MS-46; I.P. Laputina, analyst); 3-$(Pt_{0.88}Pd_{0.05}Ni_{0.05})_{0.98}S$ (MS-46; I.P. Laputina, analyst); 4-5---Braggite: 4-$(Pt_{0.50}Pd_{0.32}Ni_{0.18})_{1.00}S$ (MS-46; I.P. Laputina, analyst); 5-$(Pd_{0.51}\ Pt_{0.24}\cdot Ni_{0.21})_{0.96}S$ (MS-46; I.P. Laputina, analyst); 6-7---Vysotskite: 6-$(Pd_{0.75}Ni_{0.23}Cu_{0.01})_{0.99}S$ [105]; 7-$(Pd_{0.74}Ni_{0.25})_{0.99}S$ [105].

Sperrylite - $PtAs_2$

Occurrence and associations. The best known and most widely distributed mineral of platinum in the Noril'sk ores. Encountered 1) in impregnated ores from picrite and taxite gabbro-dolerites in the form of idiomorphic crystals measuring 0.05-1.0mm; 2) in exocontact cuproan ores in the form of crystalline grains measuring up to 0.5mm; 3) in impregnated bornite ores in the form of metacrysts or of intergrowths with Pd_2SnCu; 4) in massive pyrrhotite and chalcopyrite-pyrrhotite ores in the form of regularly shaped crystals (up to 0.7mm) and extremely thin veinlets around agglomerations of galena (Plate XVII,f); 5) in massive talnakhite and chalcopyrite ores in the form of regularly shaped crystals (up to 0.5mm) or veinlets (0.1 x several mm) in intergrowth with ferroplatinum, polarite and $(Pt,Pd)_2(As, Sb, Sn)$; 6) in massive cubanite-talnakhite and chalcopyrite-cubanite ores in the form of crystals measuring up to 1mm, in intergrowth with paolovite, sobolevskite and native silver; 7) in all the mineral varieties of breccioid ores in the form of small (30-70μm) crystals; and 8) in galena-chalcopyrite veins branching off the upper selvage of the ore bodies; it occurs here in the form of large crystals (up to 1.3cm), sometimes in intergrowth with maslovite*, froodite, native silver, sobolevskite, altaite and hessite.

Optical properties. Crystals of a tin-white colour. In reflected light white with a barely perceptible bluish tint. Isotropic. Reflectance (R,%) for 440, 460, 480, 500, 520, 540, 560, 580, 600, 620, 640, 660, 680, 700, 720 and 740 are 54.6, 54.1, 53.6, 52.6, 53.1, 52.8, 53.0, 52.9, 52.8, 52.9, 52.4, 51.6, 51.5, 51.0, 50.5 and 50.7, respectively.

Chemical composition. For most of the samples analysed Pt - 56.0 and As - 43.5 (wt %). Sperrylite from ore veins of the Noril'sk deposit contains up to 3 wt % Sn and 1%Rh. Samples from the Mayak and Oktyabr'skii mines invariably contain Rh (0.05 - 0.1 wt %) and Ir (up to 0.1 wt %). There has occasionally been observed up to 0.45 wt % Sb. The formula is close to the ideal $PtAs_2$ (MS-46; I.D. Marchukova, analyst). p.134

X-ray data. Structure of the type of pyrite. Space group Pa3, a_0=5.967Å. Principal lines of the X-ray diffraction pattern: 2.98(5)(200); 2.11(6)(200); 1.800(10)(311); 1.723(4)(222); 1.371(5)(331); 1.335(6)(420); 1.219(6)(422); 1.149(10)(513, 333); 1.057(6)(440); and 0.996(8)(600).

Hollingworthite - (Rh, Pt, Ru, Ir)AsS

Occurrence and associations. Discovered originally at the Driekop deposit, South Africa [277 and 280]. Found at the Onverwacht deposit [26]. Identified at the Noril'sk deposit in selvages of chalcopyrite veins in the form of small regularly shaped crystals (3-5μm or 30-70μm) amidst sperrylite [20] (Plate XVII,f).

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* "malovite" in the Russian text. Probably a misprint. Translator.

Optical properties. Under the microscope greyish-white with a bluish tint. Isotropic. Reflectance (R,%): 440nm. - 50.5; 460 - 51.5; 480 - 51.6; 500 - 51.7; 520 - 52.1; 540 - 52.5; 560 - 52.6; 580 - 52.0; 600 - 51.7; 620 - 51.6; 640 - 51.0; 660 - 50.1; 680 - 49.6; 700 - 49.2; 720 - 48.7; and 740 - 48.0.

Chemical composition. Rh - 25.0; Pt - 20.0; Ir - 5.0; Ru - 4.0; As - 35.0; S - 11.0; Σ - 100 (wt %). (MAR-1; N.V. Troneva, analyst).

Formula: $(Rh_{0.70}Pt_{0.30}Ru_{0.11}Ir_{0.08})_{1.19}As_{1.36}S_{1.0}$.

X-ray data. Structure of the type of pyrite. Space group Pa3, a_o=5.82Å. Principal lines of the X-ray diffraction pattern: 3.36(10)(111); 2.91(10)(002); 2.60(7)(012); 2.375(8)(112); 2.059(9)(022); 1.752(10)(113); 1.675(6)(222); 1.610(6)(023); 1.550(6)(123); 1.332(6)(133); 1.299(7)(024); 1.269(1)(124); and 1.187(7)(224).

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Genkin A.D.

SUL'FIDNYE MEDNO-NIKELEVYE RUDY NORIL'SKIKH MESTOROZHDENII //

// COPPER-NICKEL SULPHIDE ORES OF THE NORIL'SK DEPOSITS

(SECOND INSTALLMENT)
Pages 264-446

Canada

CHAPTER 3

TYPES OF COPPER-NICKEL SULPHIDE ORES

Copper-nickel ores are represented at the Noril'sk deposits by three main types: 1) Impregnated ores in intrusive rocks; 2) Massive ores in endo- and exocontacts of stratified intrusions; and 3) Veinlet-impregnated and brecciated ores in endo- and exocontact rocks of intrusions (see Table 12). Each of these types has its own characteristic patterns of distribution in space, relations with the host rocks, specific textures and structures.

IMPREGNATED ORES IN DIFFERENTIATED INTRUSIONS

Textural and structural characteristics

The characteristics of the sulphides impregnated in differentiated intrusions are determined to a large degree by the texture of the magmatic rocks enclosing the ores. The impregnation in picrite gabbro-dolerites is commonly of two types: in the form of small (0.1mm to 3mm) insets in interstices of silicate minerals, or of relative large (2-4 to 40mm or larger) drops (Plate XVIII,a and c).

The ores impregnated in taxite gabbro-dolerites are represented by large (40-80mm) or small (2-5mm) sulphide aggregates that are xenomorphic relative to the silicates (Plate XVIII, b).

Troctolite gabbro-dolerites contain a fine, sometimes fairly abundant interstitial impregnation, among which there may be encountered larger, isometric, occasionally flattened out, randomly scattered phenocrysts.

The sulphide impregnation characteristic of equigranular olivine-containing gabbro-dolerites, is of the fine interstitial type that may change to the sideronitic kind (Plate XVIII,d).

The character of impregnation varies, however, not only from one differentiate to another, but even within each one of them. This is particularly well observable in the section of picrite gabbro-dolerites and is less obvious in the taxite variety of gabbro-dolerites. A fairly sparse interstitial impregnation of sulphides occurs in the upper part of the picrite horizon. Downward in the section the interstitial impregnation increases in quantity and there appear isolated drop-like insets measuring 5mm or less. Farther down the insets increase in both number and size (first to 10-20mm, then to 40mm along the long axis). It has been observed that the zones abounding in drop-like insets, alternate with zones containing virtually no such insets and enclosing only an interstitial impregnation.

A feature characteristic of the drop-like insets in picrite gabbro-dolerites is the presence at their boundaries of idiomorphic pyroxene and plagioclase crystals projecting into the sulphide insets. Olivine is commonly absent at the contact with the insets. The sulphides impregnated in the interstices of these rocks fill for the most part the interspaces between the olivine grains and are less often in direct contact with plagioclase or pyroxene (Plate XVIII, c). The drop-like impregnation may change to the interstitial type, but the sulphide-silicate relations remain as described above. p.136

The internal structure of the drop-like insets is highly characteristic [76]. The insets are almost invariably layered because chalcopyrite composes their upper part, while pyrrhotite is disposed at the bottom. The chalcopyrite-pyrrhotite interface is commonly subparallel to the base of the picrite gabbro-dolerite horizon. Above the upper part of the insets there may be encountered fringes of non-metallic minerals, such as plagioclase, monoclinic or rhombic pyroxene, garnet, magnetite, ilmenite, apatite, prehnite, talc, chlorite, serpentinite, zeolites, calcite or anhydrite [42, 21 and 71].

The sulphide aggregates specific of picrite gabbro-dolerites are of the type of impregnation in plagioclase and plagioclase-pyroxene concentrations known in the literature as leucocratic.

Most of these leuococratic agglomerations contain, as a rule, insets of sulphides, but may also be free of them. The agglomerations are readily observable macroscopically due to their light colouring, and they sharply stand out against the background of the dark picrite gabbro-dolerites. The leucocratic agglomerations are composed largely of plagioclase and monoclinic pyroxene, the grains of which are here considerably larger than in picrites. The agglomerations may vary in size and shape from units virtually unidentifiable under the microscope to spherical formations measuring several tens of centimetres in diameter. Leucocratic agglomerations have been encountered throughout the picrite section, but their largest concentration is confined to the bottom portion of that horizon near its boundary with taxite gabbro-dolerites.

The quantity of sulphides in the leucocratic agglomerations and the size of their insets vary within a large range. In some of them sulphides amount up to 30% of individual agglomerations and form a sulphide-plagioclase type of rock in which the sulphides fill the interstices between the large plagioclase crystals. The sulphide particles vary in size from fractions of a millimetre to several centimetres.

The impregnation characteristic of taxite gabbro-dolerites is mainly in the form of large xenomorphic insets. The sulphide impregnation may gravitate towards the relatively leucocratic loci in the rock. Wherever the silicate material is observably banded or has a definite orientation, the sulphides form elongated particles subparallel to these elements.

Small particles of sulphides play a secondary role. They are found in small numbers throughout the section of taxite gabbro-dolerites, but the bottom part of the horizon that is composed of equigranular rocks, is the only place where the sulphide impregnation is represented entirely by small interstitial insets.

The sideronitic ores occurring in equigranular olivine-containing gabbro-dolerites are represented by fine interstitial insets (0.1-1-2mm). Locales with densely impregnated ores alternate in the section with those poor in mineral concentrations. Large xenomorphic phenocrysts of sulphides occur alongside the interstitial impregnation of sulphides only in the upper part of the horizon, at the contact with taxite gabbro-dolerites.

The ores impregnated in differentiated intrusions are thus essentially of three structural-morphological types of sulphide impregnation: 1) Drop-like insets in picrite gabbro-dolerites with the interstitial impregnation playing a secondary role; 2) Large-grained xenomorphic phenocrysts in taxite gabbro-dolerites; and 3) Sideronitic and interstitial impregnation in equigranular olivine-containing and troctolite gabbro-dolerites.

Mineral varieties and principal associations.

The ores impregnated in differentiated intrusions vary in mineral composition.

Their principal minerals are pyrrhotite, troilite, pentlandite, cubanite, as well as minerals of the chalcopyrite group. Among their accessory minerals there have been encountered small p.137 quantities of mackinawite, pyrite, galena, sphalerite, bornite and valleriite, and their rare minerals are represented by argentopentlandite, cuproan pentlandite and minerals of noble metals.

The diversity of ore minerals in the intrusions is determined by the varied, but strictly definite combinations of the principal ore-forming sulphides. The mineral varieties identified are as follows (Table 47): chalcopyrite-pyrrhotite, cubanite-chalcopyrite-troilite-pyrrhotite and cubanite-chalcopyrite (talnakhite, mooihoekite, cubic chalcopyrite)-troilite.

TABLE 47

Mineral varieties and associations of sulphides in impregnated ores

Mineral varieties	Mineral associations	The main horizon of localization
Chalcopyrite-pyrrhotite	$Pn+Cp+Po_m$ $Pn+Cp+Po_{m+h}$ $Pn+Cp+Po_h$ $Pn+Po(Po_h,Po_{h+m})+Cp$	Picrite and taxite gabbro-dolerites
Cubanite-chalcopyrite-troilite-pyrrhotite	$Pn+Cub+Cp+Po_h$ $Pn+Cub+Cp+Tr+Po_h$ $Pn+Cub+Cp+Po_h+Tr$	Picrite, rarely taxite gabbro-dolerites
Cubanite-chalcopyrite (talnakhite, mooihoekite, cubic chalcopyrite)-troilite	$Pn+Cub+Cp+Tr$ $Pn+Cub+Tn(Mh, Cp_c)+Tr$	Picrite gabbro-dolerites

Chalcopyrite-pyrrhotite ores are the most abundant ore variety in differentiated intrusions and amount to 40-60% of the total volume of impregnated ores in these rocks. Moreover, these ores are associated largely with taxite gabbro-dolerites and are somewhat less widely distributed in picrite gabbro-dolerites.

The predominant mineral in the composition of these ores is pyrrhotite (50-60%); the content of pentlandite in the ores is relatively constant (10-15%), while that of chalcopyrite varies between 12-15% and 30-35%*.

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* Here and in the rest of the text the contents of minerals are recalculated into 100% sulphides.

There have been identified two generations of pyrrhotite. Pyrrhotite I is commonly represented by large, often isometric grains with a well-defined parting. In layered drop-like insets pyrrhotite I composes as a rule the bottom portion of the insets and is separated from their upper chalcopyrite part by a border of pentlandite. The pyrrhotite is represented in these instances by one or several large crystals. In the other morphological varieties of impregnated ores chalcopyrite is distributed more uniformly throughout the pyrrhotite mass and occupies the interspaces between the grains of pyrrhotite I.

Large grains of pyrrhotite I contain pentlandite in the form of platy (lamellar) crystals or flames that are strictly parallel to the basal parting of pyrrhotite. Pentlandite may occur in intergrowths with small chalcopyrite grains. Furthermore, pentlandite overgrows the grains of pyrrhotite at their contact with chalcopyrite in the form of fringes measuring tenth fractions of 1mm in width. Large (up to 1-1.5mm) isometric porphyritic grains of pentlandite are found relatively rarely (Plate XIX, a).

Pyrrhotite II forms small-grained masses occurring in chalcopyrite in the form of veinlets. Pentlandite composes small spherical, less often veinlet-like aggregates amidst p.138
pyrrhotite II (Plate XIX, b).

Pyrrhotite is represented in the ores by its hexagonal and monoclinic modifications. There have been distinguished several mineral associations differing in the ratios of these modifications (Table 47).

Chalcopyrite may quantitatively predominate over pyrrhotite in the ores examined. This variety is commonly found in the frontal and marginal parts of intrusions, as well as in taxite gabbro-dolerites. The content of chalcopyrite in these ores is 40-65%, that of pyrrhotite is 15-40%. The predominant morphological varieties of pentlandite are porphyritic phenocrysts and fringes; lamellas (platy crystals) and flames of pentlandite in pyrrhotite are less abundant. The total content of pentlandite is 10-15%. Pyrrhotite II increases in abundance and forms concentrations of spherical or irregularly shaped particles along the margins of chalcopyrite.

Pyrite, magnetite and mackinawite are the accessory minerals identified in the chalcopyrite-pyrrhotite ores. Pyrite forms metacrysts or small-grained aggregates in pyrrhotite; it may also occur in the form of veinlets cutting across both pyrrhotite and silicates.

Magnetite intergrown with sulphides is distributed unevenly. The two characteristic forms of magnetite agglomerations are a) thin lamellar inclusions along the basal parting planes of pyrrhotite, and b) isometric or irregularly shaped grains occurring inside the sulphide insets and along their periphery.

Mackinawite has been observed in the form of slender veinlets or irregularly shaped particles occurring in pentlandite.

Cubanite-chalcopyrite-troilite-pyrrhotite ores are somewhat less widely distributed than the chalcopyrite-pyrrhotite ore variety. They are localized mainly in picrite gabbro-dolerites and are rarely confined to the uppermost parts of taxite gabbro-dolerites at the contact with the picrite horizon. The ratios of pyrrhotite, troilite, cubanite and chalcopyrite vary in these ores, as a result of which they are composed of several mineral associations (see Table 47).

The pentlandite-cubanite-chalcopyrite-pyrrhotite (hexagonal pyrrhotite) association is characterized by the appearance of lamellar crystals of cubanite I in chalcopyrite. Initially the number of the lamellas is rather small, but it gradually increases to a total of 5-7%. The other changes occurring concomitantly in the proportions of the ore-forming minerals are as follows: the amount of pentlandite found in the form of lamellas in pyrrhotite decreases somewhat, while the quantity of its relatively large porphyritic phenocrysts increases.

The pentlandite-cubanite-chalcopyrite-troilite-pyrrhotite association is characterized by the appearance in pyrrhotite of lamellar troilite inclusions. The number of troilite lamellas varies in different sulphide insets; the lamellas may unite forming vermiform bands. In isolated cases there have been recorded lenticular particles of troilite. As the content of troilite rises, the quantity of pentlandite lamellas gradually declines, while the amount of cubanite I in chalcopyrite increases attaining 10-15% of the total volume of sulphides.

Further increases in the quantity of troilite leads to its becoming the principal ore-forming mineral. The troilite to hexagonal pyrrhotite ratio may be 3:1. Moreover, the lamellar inclusions of pentlandite in pyrrhotite disappear and pentlandite is found mainly in the form of fringes or porphyritic phenocrysts. The second generation of cubanite, i.e. granular cubanite II, appears in chalcopyrite alongside lamellar cubanite (Plate XIX,c). It composes veinlets cutting across both pyrrhotite and chalcopyrite; it may also occur either in the form of independent particles, or in intergrowths with small-grained pyrrhotite II and pentlandite, or it may form finely granular aggregates of pyrrhotite and chalcopyrite grains replacing both these minerals. Changes of this type in the proportions of minerals account for the transition to the pentlandite-cubanite-chalcopyrite-pyrrhotite-troilite association. p.139

The troilite-pyrrhotite-cubanite-chalcopyrite and pyrrhotite-troilite-chalcopyrite-cubanite associations are less common. Their principal ore-forming minerals are chalcopyrite and cubanite found in rather widely variable proportions. Chalcopyrite predominates in some cases, cubanite in others.

Minerals of the pyrrhotite group represented by intergrowths of hexagonal pyrrhotite with troilite, form isolated isometric grains or agglomerations of small grains amidst chalcopyrite or amidst granular masses of cubanite.

Cubanite forms granular masses and veinlets (cubanite II) cutting across chalcopyrite and pyrrhotite group minerals, or develops in the form of lamellas in chalcopyrite (cubanite I).

Pentlandite forms porphyritic phenocrysts and occurs in negligibly small quantities in the form of fine-grained aggregates in cubanite.

We may thus see a gradual transition from the chalcopyrite-pyrrhotite to the cubanite-chalcopyrite-troilite-pyrrhotite association in impregnated ores: the content of troilite in the troilite-pyrrhotite intergrowths progressively increases, lamellar pentlandite decreases in quantity until it disappears completely, and the cubanite : chalcopyrite ratios alters. The ores, in which chalcopyrite predominates, may contain granular cubanite II.

Cubanite, chalcopyrite (talnakhite, mooihoekite, cubic chalcopyrite)-troilite ores are the least widely distributed type of impregnated ores and amount to 5% or less of their total volume. These ores occur mainly in the thickest central locales of intrusive massifs and are confined to the middle of the picrite gabbro-dolerite horizon. These ores have not been encountered in any of the other differentiates of the intrusions.

Impregnated ores composed of the cubanite-chalcopyrite-troilite association, form gradual transitions to the cubanite-chalcopyrite-pyrrhotite-troilite ores. The only mineral of the pyrrhotite group encountered in the former is troilite, which predominates over the other ore-forming minerals. It is represented by large, occasionally isometric grains or occurs amidst the aggregates of granular cubanite II and in chalcopyrite in the form of small spherical or irregularly shaped particles. The content of troilite in different insets amounts to 40-70%. Pentlandite is found mainly in the form of porphyritic phenocrysts, less often in the form of borders filling the intergranular spaces in troilite; it also forms fine-grained aggregates in cubanite II. No lamellas of pentlandite are found in troilite.

The content of chalcopyrite in the ores may vary fairly widely (20 to 40%). Cubanite I is invariably present in chalcopyrite in the form of lamellas or tabular crystals; the ratios of these minerals are highly variable. In some of the insets chalcopyrite predominates over cubanite, while in others cubanite predominates over chalcopyrite.

A characteristic feature of the pentlandite-cubanite-talnakhite (mooihoekite, cubic chalcopyrite)-troilite association is the presence in it of talnakhite, mooihoekite and cubic chalcopyrite instead of the usual tetragonal chalcopyrite. Until recently these minerals were known only from massive ores [150], but it has now been established [61] that they also occur in stratified intrusions of the Noril'sk region.

In contrast to massive ores, in impregnated ores minerals of the chalcopyrite group are constantly associated with troilite, which always predominates quantitatively over the other sulphides.

It should be noted that in impregnated ores it is impossible to identify locales in which one of the chalcopyrite group minerals predominates. These minerals almost always form intergrowths and may be found in them in variable quantities. Homogeneous particles of individual minerals from that group have been encountered much less often. p.140

Talnakhite commonly occurs in the ores in fine intergrowths with tetragonal chalcopyrite, which forms regularly oriented lense-shaped lamellas in talnakhite. The quantity of these lamellas varies widely. In some instances tetragonal chalcopyrite predominates and talnakhite forms small vermiform or lamellar particles in it. Homogeneous grains of talnakhite have been encountered extremely rarely. Mooihoekite has been observed in association with talnakhite less often. It occurs in talnakhite in the form of lamellas or tabular crystals (15-30 um in width) with sharp boundaries and split, sometimes lanceolate ends. Mooihoekite and talnakhite may form aggregates, in which lamellas of the two minerals alternate in succession.

Cubic chalcopyrite forms polysynthetic twin grains (Plate XIX,d) enclosing sparse lamellas (0.1x0.02mm) of talnakhite and lenticular crystals of pentlandite.

Mooihoekite and cubic chalcopyrite occur in the form of closely intergrown grains with indistinct diffuse boundaries, or of aggregates composed of series of parallel lamellas similar to polysynthetic twins.

Cubanite I forming lamellas or tabular crystals measuring a few microns to fractions of a millimetre in width, has been encountered in the insets composed of chalcopyrite group minerals.

Granular cubanite II occurs in the form of borders around porphyritic phenocrysts of pentlandite or magnetite, as well as of veinlets in minerals of the chalcopyrite group and in troilite. The veinlets may gradually change to loci composed of an inequigranular aggregate of cubanite.

Pentlandite is represented in these ores by large porphyritic phenocrysts and is present in minerals of the chalcopyrite group in the form of small lenticular grains.

The most widely distributed late minerals are valleriite, mackinawite and cuproan pentlandite replacing minerals of the chalcopyrite group and pentlandite.

Zoning and cryptic layering

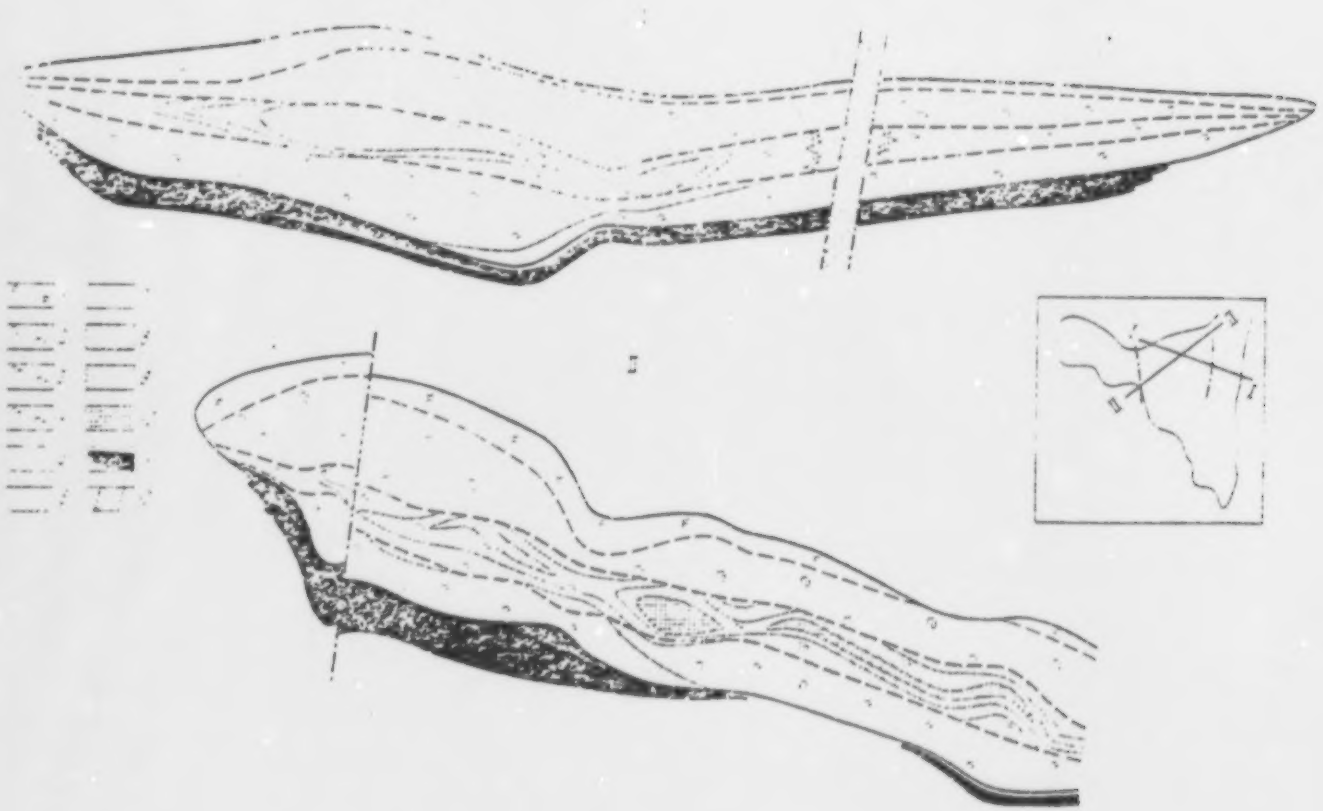
The mineral associations described above are localized in differentiated intrusions mainly in the lower part of the massifs. The distribution of mineral varieties of ores follows a systematic pattern in the section of different horizons, as a result of which there arises a specific zoning of sulphide ore deposits in these intrusions.

Impregnated sulphide ores have the most complex composition in picrite gabbro-dolerites. All the associations discussed above may be encountered within one single horizon. The composition of impregnated ores gradually grows more complex along the horizontal from the periphery of this horizon to the central parts of the massif.

The chalcopyrite-pyrrhotite association develops in the frontal and marginal parts of the horizon. Pyrrhotite is represented in that association by its monoclinic modification. Towards the central parts of the massif (fig.25) hexagonal pyrrhotite replaces monoclinic pyrrhotite in the ores. It is often possible to trace the gradual transition marked by the appearance of intergrowths of the monoclinic and hexagonal modifications and by the subsequent disappearance of the former. Farther down the strike the chalcopyrite-pyrrhotite association is succeeded by the pentlandite-cubanite-chalcopyrite-pyrrhotite and pentlandite-cubanite-chalcopyrite-troilite-pyrrhotite associations, while associations with troilite, talnakhite and mooihoekite appear in the central parts of the intrusions. As may be seen from fig.25, the latter assemblages are confined to the central parts of the picrite gabbro-dolerite horizon. p.141

A regular succession of mineral associations has also been observed in the vertical section. Complete zoning can be traced in fig. 25. Impregnated pentlandite-chalcopyrite-pyrrhotite ores may be encountered in the uppermost parts of the picrite gabbro-dolerite horizon and at the base of the horizon of olivine-biotite gabbro-dolerites. The ores represented by tetragonal p.142 chalcopyrite intergrown with lamellar cubanite and hexagonal pyrrhotite, are localized below that level. These ores are succeeded by impregnated cubanite-chalcopyrite-troilite-pyrrhotite sulphides that are characterized by the appearance of lamellar troilite in hexagonal pyrrhotite, and by cubanite-chalcopyrite-pyrrhotite-troilite ores, in which cubanite is invariably represented by two generations. Troilite predominates in its intergrowths with hexagonal pyrrhotite. The ores composed of troilite, talnakhite and mooihoekite are confined to the central part of the horizon. These ores appear mainly in the locales, where the picrite horizon has the greatest thickness.

Fig. 25



Distribution of mineral associations of sulphides in vertical sections of the Talnakh differentiated intrusion

The position of sections I and II is shown diagrammatically in the inset. 1-Diorite, gabbro-diorites, gabbro; 2-Olivine-free, olivine-containing and olivine gabbro-dolerites; 3-Picrite gabbro-dolerites; 4-Taxite gabbro-dolerites; 5-10---Mineral associations of sulphides; 5-Pn+Cp-Po; 6-Pn+Cp+Po; 7-Pn+Cub+Cp+Po; 8-Pn+Cub+Cp+Tr+Po_h; 9-Pn+Cub-Cp+Tr; 10-Pn+Cub-Tn (Mh, Cp)+Tr; 11-Bodies of massive sulphide ores; 12-Disturbances with dislocation (ruptures).*

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* The formulas are poorly legible in the Xerox copy. Translator.

Downwards from the central part of the horizon of picrite gabbro-dolerites the sequence of the mineral associations is reversed (fig. 25), which accounts for the symmetrical pattern of distribution. It is important to emphasize that depending on the position of vertical sections in space, there may be encountered sections along the strike with different combinations of mineral associations, but the ores with troilite, cubanite, talnakhite and mooihoekite will always be confined to the central part of the picrite horizon.

As has already been noted in the literature [40, 61], in the horizon of picrite gabbro-dolerites the mineral composition of the sulphide aggregates belonging to different morphological types may vary even within the same sample. The mineral composition of interstitial ores may differ from that of ovoid insets. Impregnated interstitial ores may be composed of troilite, while the nearby ovoid insets may be represented by intergrowths of troilite and hexagonal pyrrhotite. If both types of impregnated ore are represented by intergrowths of troilite and hexagonal pyrrhotite, the number of troilite inclusions is distinctly greater in the interstitial agglomerations of sulphides than in pyrrhotite of the ovoid insets. If these samples also contain leucocratic particles, then they are composed of different mineral associations of sulphides. The possible correlations are as follows: 1) The cubanite-chalcopyrite-troilite (+hexagonal pyrrhotite) association is present in picrites, while the chalcopyrite+hexagonal pyrrhotite association is found in leucocratic agglomerations; or 2) Chalcopyrite (± cubanite)+hexagonal pyrrhotite is present in picrites, and chalcopyrite+monoclinic pyrrhotite in leucocratic particles.

The transitional zone between the picrite and taxite kinds of gabbro-dolerites is the characteristic boundary in the succession of sulphide mineral associations (fig. 25). In sections from the central part of the intrusive massif, in the uppermost part of taxite gabbro-dolerites, there may be encountered pentlandite-cubanite-chalcopyrite-troilite-pyrrhotite ores, while cubanite-chalcopyrite-pyrrhotite ores with hexagonal pyrrhotite and lamellar cubanite may occur farther down in the section. The horizon of taxite gabbro-dolerites is generally characterized by the predominant development of chalcopyrite-pyrrhotite ores with hexagonal or, less often, monoclinic pyrrhotite that is more common in the lower part of the horizon and in the flanges of intrusive massifs.

The zoning of ore deposits described here is manifest in a regular succession of different associations of ore minerals and in their being confined to strictly definite parts and horizons of stratified intrusive massifs. It represents the macrostratification of sulphide ores. An equally important characteristic of impregnated mineral deposits is cryptic layering of sulphide ores reflecting the systematic variations in the composition of the co-existing sulphides determined by their paragenesis.

Pyrrhotite, pentlandite and minerals of the chalcopyrite group are among the minerals with a variable composition in impregnated ores. It has been recently established that pentlandite varies widely in composition in the ores of the Noril'sk region, and that the content of nickel in minerals of the pyrrhotite group varies within a large range on account of variations in their sulphur contents [40, 154, 115, 116, 56 and 61]. p.143

The compositions of the minerals were determined on the basis of X-ray diffraction data and of the data from analyses with the help of an X-ray micro-analyser. Results of X-ray diffraction for pyrrhotites expressed in reflectance values for d_{102}, were recalculated with the help of Arnold's curve [169] into atom per cent of total metals (at.% ΣMe). Unfortunately the data of micro-probe X-ray analyses cannot always be used in discussing variations of d_{102} as a function of the composition of natural pyrrhotites, since the standard deviations in determinations of iron and sulphur by this method often fail to ensure the level of precision required for solving this problem.

Recalculations of the analyses (Table 48) and juxtaposition of the atomic proportions metal/sulphur (Me/S) obtained with the d_{102} value reveal nevertheless a definite correlation between them in that greater Me/S values in pyrrhotite correspond to greater values of d_{102}.

TABLE 48

Номер образца 1	2 Пирротин						4 Пентландит				
	d_{102}	ат. % ΣMe	Fe	Ni	S	сумма 3	Fe	Ni	Co	S	сумма 5
1159/1470,2	2,09636		63,0	0,03	35,8	98,83	34,9	31,1	Не обн.	32,9	
	2,07622	48,30	62,2	0,03	38,0	100,23					
1159/1472,8	2,07690	48,30	60,5	0,41	38,0	98,91	30,2	34,2	То же	31,5	
1159/1476,1	2,07416	48,05	60,7	0,54	38,9	100,10	33,0	34,0	»	32,3	
1159/1478,4	2,07240	47,85	60,5	0,77	37,5	98,77	31,5	34,5	»	32,5	
1170/1519,6	2,07484	48,125	61,6	0,08	37,4	99,08	34,7	31,3	1,0	32,9	100,4
1170/1539,5	2,07074	47,750	60,3	0,71	38,3	99,31	29,3	35,9	1,9	32,7	99,8
1170/1544,6			59,9	0,87	39,1	99,87	28,3	37,5	2,0	32,1	100,0
1530/1552,4	2,09425		62,0		36,0	98,0	33,2	31,6	0,82	32,5	98,12
	2,07484	48,125	63,0	0,14	37,0	100,14					
1536/1559,3	2,06804	47,50	61,1	0,28	38,3	99,68	31,3	33,3	1,4	32,0	98,3
1536/1563,5			60,2	0,56	40,0	100,76	29,0	36,5	1,4	32,7	99,6
1547/1455,1	2,07008	47,675	61,9	0,33	37,8	100,03	30,4	34,5	1,2	33,9	100,0
1547/1459,1	2,07279	47,90	61,0	0,15	37,6	98,75	33,4	32,7	0,9	32,2	99,2
1547/1500,9	2,07142	47,80	63,3	0,22	36,5	100,02	34,2	32,7	1,1	32,2	100,2
1547/1564,0			59,3	0,59	38,3	98,19	28,8	37,3	1,1	32,7	99,9
6 ИС 29/545,9			63,2		36,5	99,7	34,9	30,6	0,5	34,0	100,0
6 ИС 29/548,2			63,9		36,3	100,2					
			61,2	0,08	38,2	99,48	32,8	32,5	0,6	32,6	98,5
			60,8	0,24	38,2	99,24					
6 ИС 29/552,7			63,6	0,01	36,5	100,1	33,8	32,0	0,7	33,3	99,8
7 СТ 2/142,7							37,3	23,8	0,9	33,8	100,8

Chemical composition (wt %, X-ray micro-analysis) of the coexisting pyrrhotite group minerals and pentlandite in impregnated ores
1-Sample number; 2-Pyrrhotite; 3-Total; 4-Pentlandite; 5-Total; 5-IS*; 7-ST*.

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* Transliteration. Translator.

According to the X-ray diffraction data, troilite has reflectance values for d_{102} equal to 2.0942-2.0978 (see Table 48). These reflectance values are somewhat higher than the corresponding d_{102} values of 2.0915 obtained by Arnold [169] for stoichiometric FeS, or the 2.0932 ± 0.0001 values obtained by P. Toulmin and P. Barton [282]. The high values of d_{102} may be due to a somewhat greater quantity of iron atoms versus that of stoichiometric FeS [60].

Troilite is virtually free of minor and trace components. In most of the grains analysed with the sensitivity of 0.01% or higher there have been detected no minor or trace elements or the only trace element found was nickel present in amounts of 0.03% or less.

The composition of hexagonal pyrrhotite varies in the ores within a relatively large range. The reflectance values d_{102} vary within the limits of 2.068-2.077, which corresponds to the variations of total metals equalling 47.5-48.3 at. %. Hexagonal pyrrhotite with the highest total content of metals (48.125 to 48.30 at. $\% \Sigma$Me) occurs in associations with troilite. In p.144
some instances we succeeded in observing the following pattern: the greater the troilite fraction in intergrowths with hexagonal pyrrhotite, the higher the content of iron in the latter.

The composition of hexagonal pyrrhotite varies widely (47.5-48.30 at. $\% \Sigma$Me). Pyrrhotites with 47.5-47.75 et. $\% \Sigma$Me coexist with monoclinic pyrrhotite.

The concentration of nickel in hexagonal pyrrhotite varies within the limits of 0.03-0.87% and in each specific section of the intrusion it is proportionate to the Me/S ratio in the mineral. It should be noted that the concentration of nickel may vary in pyrrhotites having identical iron contents, but belonging to different associations. The lowest nickel concentration (0.02-0.14%) has been recorded in hexagonal pyrrhotite coexisting with troilite. In many cases its concentration is the same in both phases. The concentration of nickel in homogeneous hexagonal pyrrhotite varies from 0.22 to 0.70%, while in the hexagonal pyrrhotite coexisting with its monoclinic modification the concentration of nickel may be as high as 0.85%.

Of great interest is the distribution of nickel between the monoclinic and hexagonal pyrrhotites of impregnated ores. There are two possible variants: 1) Formation of monoclinic pyrrhotite in the process of the low-temperature diffusion of hexagonal pyrrhotite [25]; or 2) Formation of monoclinic pyrrhotite as a result of the alteration or unmixing of a sulphur-rich monosulphide solid solution (Mss). In the latter instance there may arise homogeneous grains of monoclinic pyrrhotite or its intergrowths with hexagonal pyrrhotite.

Table 49 shows the contents of nickel in the coexisting minerals of the pyrrhotite group formed as a result of the processes outlined above. Trimineral intergrowths consisting of troilite, hexagonal and monoclinic pyrrhotites, appear to be of interest. The two latter minerals compose the periphery or isolated loci of the grains confined to the edges of the cracks cutting through the aggregates. Monoclinic pyrrhotite is localized in the outer zone that is succeeded by the zone of hexagonal pyrrhotite, while troilite occupies the centre of the grain. It has been established that the content of nickel increases systematically in these intergrowths from troilite to monoclinic pyrrhotite. This may be regarded as a process of p.145 redistribution and relative enrichment of the monoclinic phase by nickel in the process of removal of a portion of iron atoms from troilite and hexagonal pyrrhotite. It should be stressed that in this type of monoclinic pyrrhotite the concentration of nickel is half to a quarter that found in the monoclinic pyrrhotite modification evolved as a result of unmixing of the monosulphide solid solution.

TABLE 49

Variations in the content of nickel in the coexisting minerals of the pyrrhotite group during the low-temperature diffusion and in the process of unmixing of the monosulphide solid solution (wt %, X-ray micro-analysis)

Sample Number	Low-temperature diffusion		Sample number	Unmixing of solid solutions	
	minerals	content		minerals	Ni content
IS-29 548.2	Troilite	0.01	KZ-1159 1470.2	Troilite	0.01
	Hexagonal pyrrhotite	0.08	KZ-1159 1470.2	Hexagonal pyrrhotite Troilite	0.01 0.03
	Monoclinic pyrrhotite	0.24		Hexagonal pyrrhotite	0.03
	Troilite	0.03			
IS-29 548.2	Hexagonal pyrrhotite	0.09	KZ-401 402.0	Hexagonal pyrrhotite	0.20
	Monoclinic pyrrhotite	0.31		Monoclinic pyrrhotite	0.20
KZ-716	Hexagonal pyrrhotite	0.17	KZ-169 582.7	Hexagonal pyrrhotite	0.25
	Monoclinic pyrrhotite	0.22		Monoclinic pyrrhotite	0.14

If hexagonal and monoclinic pyrrhotites crystallize from a sulphur-rich MSS, then in the course of fractionation nickel may be divided equally between these phases (see Table 49).

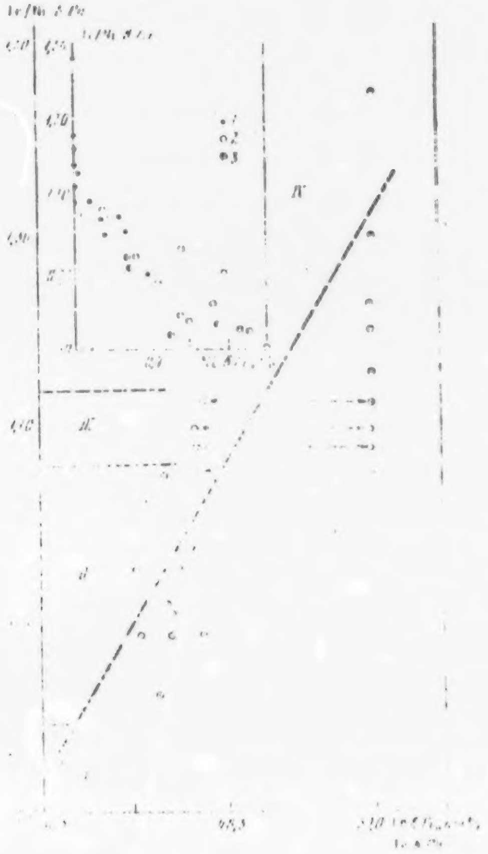
Summing up the patterns of distribution of nickel in pyrrhotite group minerals of impregnated ores, it may be inferred that troilite and the hexagonal pyrrhotite coexisting with it, have the lowest contents of nickel (0.3% or less); that its intermediate contents (3.3% to 0.4-0.5%) are characteristic of homogeneous hexagonal pyrrhotite; and that the maximum nickel contents (over 0.4-0.5%) are found in homogeneous hexagonal pyrrhotite, in the hexagonal pyrrhotite coexisting with monoclinic pyrrhotite, and in monoclinic pyrrhotite.

Chemical composition of pentlandite also varies widely in impregnated ores. The composition of pentlandite is determined by the type of its paragenetic association and by the localization of the association in definite horizons of stratified massifs. Pentlandite contains 28.3 to 37.3% Fe and 28.8 to 38.8 % Ni; its Fe/Ni ratio varies from 0.73 to 1.3 (see Table 48).

The relationship of the iron content in pentlandite and in the pyrrhotite group minerals coexisting with it, is shown in the diagram (see fig. 26). Pentlandites with the lowest iron contents (Fe/Ni $<$ 0.80) coexist with monoclinic pyrrhotite (field I). Homogeneous hexagonal pyrrhotite coexists with a pentlandite with a rather widely varying content of iron (Fe/Ni = 0.8-1.05) (field II). The pentlandite associated with the hexagonal pyrrhotite intergrown with troilite has a significantly smaller range of iron contents (1.05-1.14). The pentlandite with the ratio of its metal components above 1.14 associates with homogeneous troilite.

Variation patterns of nickel concentrations in the pyrrhotite coexisting with pentlandite are also shown in that diagram. The compositions of these minerals generally tally with regard to their nickel concentrations, although this agreement is somewhat less than linear (see the diagram in the inset of fig. 26). The deviation has been recorded mainly for the troilite+hexagonal pyrrhotite association and is due to the sharp drop in the concentration of nickel in pyrrhotite and to the widely variable composition of the pentlandite coexisting with troilite. p.146

Fig. 26



Diagrammatic representation of the compositions of the coexisting pyrrhotite group minerals and pentlandite from impregnated ores I-IV: Fields of compositions of the coexisting pentlandite and monoclinic pyrrhotite (I), hexagonal pyrrhotite (II), hexagonal pyrrhotite intergrown with troilite (III) [the compositions are linked by arrows] and troilite (IV). A correlation diagram of variations in the contents of nickel in pyrrhotite (the X-axis) is shown in the inset. FeNi in pentlandite (the Y-axis) for different horizons of the intrusions: 1-picrite, 2-taxite, and 3-contact gabbro-dolerites.

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Chalcopyrite group minerals may be divided on the basis of their composition into two subgroups: tetragonal chalcopyrite with the ΣMe/S=1 ratio; and phases with the ratio ΣMe/S$>$1,i.e.

talnakhite, mooihoekite and cubic chalcopyrite.

Tetragonal chalcopyrite is the most widely distributed mineral of that group. It has a constant composition, occurs in all the differentiates of the intrusions and coexists with the largest range of sulphides, including compositionally diverse monoclinic and hexagonal pyrrhotites, troilite and pentlandite.

Tetragonal chalcopyrite associated with troilite and iron-rich pentlandite is found in intergrowths with other minerals of the chalcopyrite group, in which $\sum \mathrm{Me/S} > 1$.

A modification of tetratogal chalcopyrite, the so-called ferroan chalcopyrite, has been identified in the ores [83]. With regard to its optic properties and structure this modification is identical to tetragonal chalcopyrite, but differs from it in its copper to iron ratio, which is 0.95:1.05, and because of the appearance of nickel (up to 0.30%) in its composition. "Ferroan chalcopyrite" occurs only in association with hexagonal pyrrhotite+troilite, homogeneous troilite and iron-rich pentlandite.

Minerals of the chalcopyrite group with $\mathrm{Me/S} > 1$ form part of the association represented by homogeneous troilite and pentlandite with the highest iron concentration ($\mathrm{Fe/Ni} > 1.14$).

The variations in the composition of the coexisting sulphides in impregnated ores are responsible for the cryptic layering of these mineral concentrations.

Fig. 27 shows a number of sections from the central and marginal parts of the Talnakh intrusion. The distribution of various associations of sulphides in different horizons of the intrusion and the patterns of variations in the composition of the coexisting pyrrhotite (according to d_{102}) and pentlandite are shown in the drawing. In the section from the marginal part of the massif (fig.27,a) composed of pentlandite-chalcopyrite-pyrrhotite ores(with monoclinic and hexagonal pyrrhotites), the variations in the contents of iron in pyrrhotite are expressed by the curve with the maximum values of iron concentration (47.90 at. %ΣMe) in the central part of the picrite horizon declining towards both its upper (47.675 at.%ΣMe) and lower (47.80 at.%ΣMe) parts.

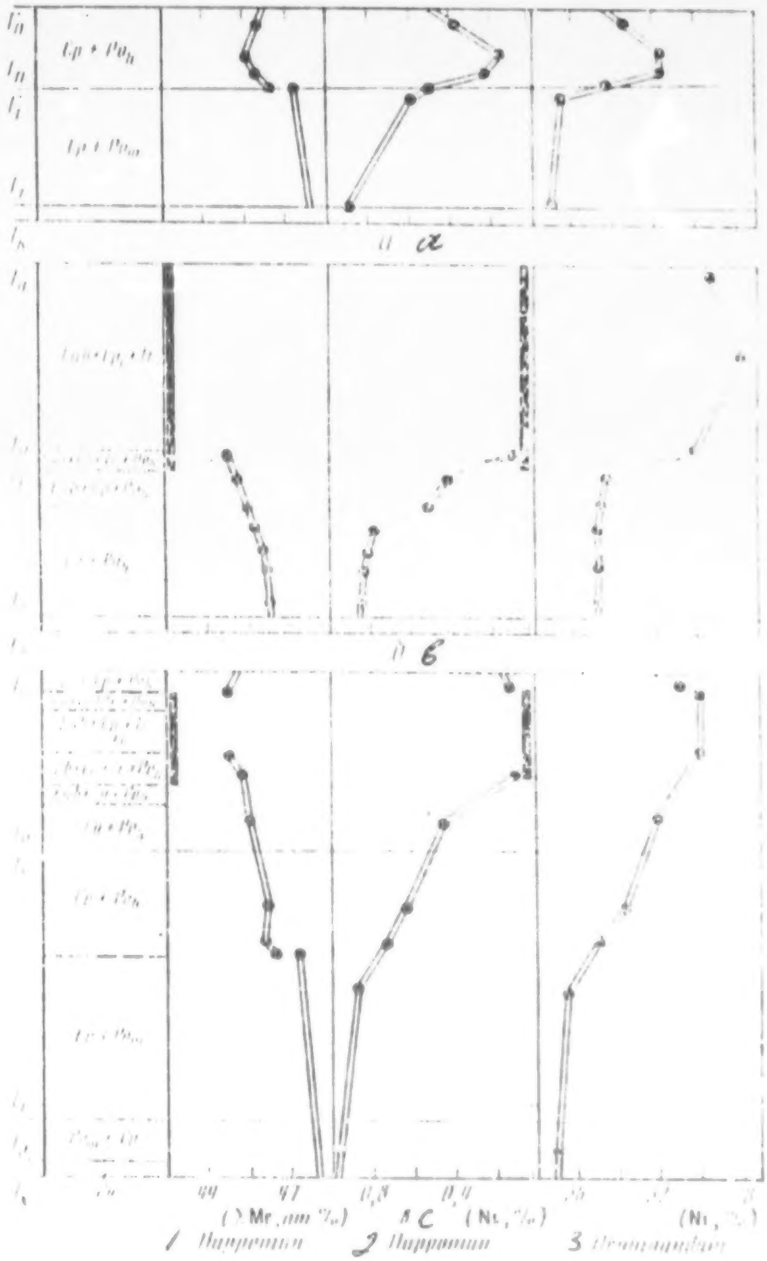
The curves illustrating the distribution of nickel in pyrrhotite and pentlandite are of a different character. The minimum values of the content of nickel in these minerals (0.15% for pyrrhotite and 31.8% for pentlandite) correspond to the nickel contents in the central parts of the picrite gabbro-dolerite horizon. These values gradually increase towards the upper and lower contacts of the picrite gabbro-dolerite horizon and are 0.4% in pyrrhotite and 34.6% in pentlandite from the upper, and 0.5% in pyrrhotite and 35.3% in pentlandite from the lower parts of the picrite gabbro-dolerite horizon, respectively. It has been established that in taxite gabbro-dolerites the content of iron in pyrrhotite decreases further towards the lower contact of the horizon, and that the nickel content in both pyrrhotite and pentlandite rises.

In sections from the central part of the intrusive massif minerals of the pyrrhotite group have constant contents of iron in the locales where the ores contain troilite (fig. 27,b). Pentlandite with the minimum nickel concentrations (28% in the central part of the picrite gabbro-dolerite horizon) occurs in intergrowths with troilite having the maximum d_{102} values. Towards the upper and lower parts of the sections, in which homogeneous troilite occurs, the concentration of nickel in pentlandite increases to 30% and 31.2%, respectively. p.147

In impregnated ores with paragenetic sequences containing nickel-free troilite, cryptic layering thus manifests itself only in the composition of pentlandite (fig. 27,b).

Towards the lower endocontact of the intrusion (fig.27,b), as there appear first of all associations with troilite-hexagonal pyrrhotite intergrowths, then assemblages with homogeneous hexagonal pyrrhotite, the concentration of iron in hexagonal pyrrhotite decreases from 48.3 to 47.6 at.% $\sum$Me, while the content of nickel in pyrrhotite and pentlandite rises to 0.83% and 34.8%, respectively.

Fig. 27



Distribution of mineral associations of sulphides and cryptic layering of sulphide ores in sections from the flanges (a), central (b) and intermediate (c) parts of the Talnakh differentiated intrusion. 1-Pyrrhotite; 2-Pyrrhotite; 3-Pentlandite.

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p.148

In the section (fig. 27,c) intermediate between the marginal and central parts of the intrusive massif, there have have been established analogous patterns of variations in the composition of minerals from the groups of pyrrhotite and pentlandite.

MASSIVE ORES

The main compositional characteristics and mineral varieties of the ores

Massive ores are known from many different deposits and mineral occurrences of the Noril'sk province, but the largest amounts of massive ores occur at the Talnakh ore field and Noril'sk I deposit. In most of the deposits massive ores have a relatively simple composition with a limited number of the principal constituent ore minerals. These minerals include members of the pyrrhotite group, tetragonal chalcopyrite, pentlandite and magnetite that is invariably associated with sulphides. At the Talnakh ore field and at the Noril'sk I deposit there is a greater variety of ore-forming sulphides. In addition to the principal minerals listed above, these ores comprise talnakhite, mooihoekite and cubanite. Some of the accessory minerals, such as troilite and cubic chalcopyrites, are widely distributed. Unlimited variations in proportions of the principal sulphides and in their associations account for an unusually great diversity of the mineral varieties of ores linked by gradual transitions. Their systematic distribution in space results in a specific mineral zoning of the ore bodies. There have been distinguished five mineral varieties among these ores on the basis of their predominant constituent ore mineral: pyrrhotite, cubanite, chalcopyrite, talnakhite and mooihoekite ores. All these varieties are known to occur at the

Talnakh ore field, and the first four are also found at the Noril'sk I deposit. Within each of the mineral varieties there have been identified several transitional varieties, the names of which include two or three genetically important accessory minerals (Table 12).

In terms of the relative abundance, pyrrhotite ores predominate at the Talnakh, Oktyabr'skii and Noril'sk I deposits. In deposits of the Talnakh ore field other major ore varieties, such as talnakhite, mooihoekite, cubanite or chalcopyrite ores, as well as their transitional varieties, may compose, however, substantial parts of individual massive ore deposits.

Pyrrhotite ores have a relatively simple composition. Their typical constituent minerals are pyrrhotite represented by its monoclinic and hexagonal modifications, tetragonal chalcopyrite, pentlandite and magnetite. Cubanite is present very rarely, mainly in the ores transitional to the chalcopyrite variety, and occurs in the form of regularly oriented lamellas in chalcopyrite. Minerals of platinum and late sulphides of iron, i.e. pyrite and mackinawite, have been detected in the form of isolated agglomerations.

Pyrrhotite sharply predominates over the other ore minerals. Its relative content varies depending on the quantity of non-metallic inclusions.

The fabric (texture and structure) of the ores is determined by the proportions of the principal ore minerals and by the presence (or absence) of non-metallic inclusions. On the basis of these features there have been distinguished two varieties of pyrrhotite ores: 1) The ores with a massive or knitted texture (Plate XX,a) in which the relative content of non-metallic inclusions is nil or no greater than 5-7% of the total sulphides; and 2) the ores with the content of non-metallic inclusions varying between 10 and 30%. Ores of the latter variety display a greater diversity of structures depending on the composition, quantity and shape of their non-metallic inclusions: p.149

they may be maculose (Plate XX,b), here and there banded, and in the periphery of the ore bodies - densely impregnated. The ores of the first variety occur in intrusive rocks, as well as in the sedimentary-metamorphic wall rocks. The ores of the second variety occur exclusively in sedimentary-metamorphic rocks forming, in combination with massive ores, fairly thick deposits that are most extensively developed at the Talnakh ore field. A characteristic feature of this type of deposits is that they form sharp, but extremely sinuous contacts with their host rocks with a multitude of sulphide embayments and with the rocks projecting into the sulphide mass (Plate II,b). The sulphide aggregates retain here and there the texture of the rocks replaced by them.

Massive ores are composed of inequigranular aggregates of pyrrhotite with knitted agglomerations of chalcopyrite filling the interspaces between them. There have been distinguished two morphological modifications of pyrrhotite in the sulphide aggregates. Pyrrhotite I that is represented by large grains varying in size from 0.5mm to 3-5m and attaining in places 10-15cm, sharply predominates. Pyrrhotite II that forms fine-grained aggregates with the grains measuring 0.1-0.2mm or less, is found in subordinate quantities. Large grains of pyrrhotite I with lamellar inclusions of pentlandite or, less often, of chalcopyrite along the basal parting, randomly alternate with aggregates of smaller (0.5-2mm) isometric grains closely intergrown with magnetite (Plate XX,c). Skeletal or spherical magnetite grains are disposed in the interspaces between the grains of pyrrhotite (Plate XX,d) or amidst chalcopyrite at its boundaries with pyrrhotite. Graphic intergrowths of pyrrhotite and magnetite may occasionally be observed in the periphery of large pyrrhotite grains. Furthermore, magnetite occurs in pyrrhotite I in the form of isolated idiomorphic inclusions (up to 1mm) or slender lamellas confined to the basal parting planes of pyrrhotite (Plate VIII,d). The grains of magnetite often contain spherical agglomerations of sulphides. Relations of this type evidence that magnetite and pyrrhotite crystallized together. It should be noted that pyrrhotite ores may also contain later agglomerations of magnetite that are represented by veinlets cutting across pyrrhotite, chalcopyrite and pentlandite.

Pentlandite occurs in massive ores mainly in the form of lamellar inclusions in pyrrhotite grains, of flames along their cracks or of fringes around the periphery of these grains at their boundaries with chalcopyrite, or around the magnetite grains. Fringes of pentlandite at the boundaries with chalcopyrite expand in places (in the loci with increased contents of chalcopyrite) changing to larger (up to 0.3-1.0mm) agglomerations. Isometric grains (up to 0.5mm) occur in the form of inclusions in pyrrhotite.

The content of chalcopyrite varies in these ores. The boundaries of chalcopyrite with pyrrhotite I grains may be either straight or undulate, with deep embayments of chalcopyrite along the cracks or along the basal parting of pyrrhotite. The lamellas of pentlandite and magnetite enclosed in pyrrhotite, extend then without any disturbances into chalcopyrite. Amidst the agglomerations of chalcopyrite there have been encountered islets of pyrrhotite having the same orientation as the pyrrhotite grains adjoining chalcopyrite. All this testifies that chalcopyrite crystallized later than pyrrhotite I and partly replaced the latter. Concentrations of fine-grained pyrrhotite II may be observed in the periphery of pyrrhotite I grains near their boundaries with chalcopyrite, and are separated from the grains of pyrrhotite I by discontinuous borders or chains of pentlandite grains. Minutest pentlandite grains (up to 0.01mm) form numerous inclusions in aggregates of pyrrhotite II. Veinlets and spotty concentrations of allotriomorphic aggregates of pyrrhotite II have also been encountered in chalcopyrite.

Pyrrhotite ores with silicate inclusions differ from massive ores because of their heterogeneity. Variously shaped non-metallic inclusions measuring fractions of a millimetre to 10-15cm may be distinguished in these ores against the background of sulphide aggregates. The inclusions vary widely in composition depending on the composition of the rocks hosting the ore deposits.

They are composed predominantly of apoargillite hornfels p.150 (chlorite-feldspar, biotite-pyroxene or biotite-feldspar hornfels with hypersthene, quartz and apatite), quartz-containing plagioclase-potash feldspars with wide-spread graphic quartz-feldspar intergrowths, and other rocks.

Sulphide aggregates have a finer-grained texture than massive ores. Their relative content of pyrrhotite is 60% or less. Isometric grains of pyrrhotite measuring 2-3mm or less, are surrounded by slender (0.1mm), even borders of pentlandite (Plate XX,d). Lamellar inclusions of pentlandite in pyrrhotite are relatively rare. Veinlets of chalcopyrite and small (0.5mm) isometric grains of magnetite fill the interspaces between the pyrrhotite grains. In isolated loci the content of magnetite attains 10-20%. Concentrations of magnetite grains are commonly confined to silicate inclusions, where magnetite may predominate over sulphides. Magnetite together with chalcopyrite forms fringes around the silicate inclusions. In some places the original shape of the latter can be determined only thanks to the concentrations of magnetite and chains of its grains bounding the inclusions. It is characteristic that, in addition to magnetite, there has been encountered in these ores titanomagnetite with lattice exsolution textures of platy ilmenite crystals.

Monoclinic and hexagonal pyrrhotites are present in both structural varieties of ores. They occur separately, but may also be found in close intergrowths. In isolated locales, mainly at the contacts with cubanite ores, there has been encountered troilite that also occurs in close intergrowths with hexagonal pyrrhotite. Hexagonal pyrrhotite of a variable composition predominates in most deposits of massive pyrrhotite ores.

There have been distinguished [illegible]opyrite-pyrrhotite and troilite-pyrrhotite mineral varie[illegible]f pyrrhotite ores.

Chalcopyrite-pyrrhotite ores are a variety intermediate between the pyrrhotite and chalcopyrite varieties of ores. They differ from pyrrhotite ores because of their higher contents of chalcopyrite (up to 30%) and pyrrhotite II; the latter forms veinlets and irregularly shaped agglomerations in chalcopyrite. The transition from pyrrhotite ores to the chalcopyrite-pyrrhotite ore variety is gradual: the intergranular agglomerations of chalcopyrite grow progressively larger, while pyrrhotite I decreases in quantity and occurs in the form of isolated grains scattered throughout the chalcopyrite mass. The particles of pentlandite alter in shape and pentlandite is represented in chalcopyrite by relatively large grains (up to 1-2mm). The grains of chalcopyrite contain in some places regularly oriented lamellas of cubanite that is lacking in common pyrrhotite ores.

Troilite-pyrrhotite ores are close in texture and structure to the pyrrhotite variety of ores, but differ from the latter because of the presence of troilite, granular cubanite, and greater numbers of larger porphyritic phenocrysts of pentlandite. Troilite has been observed only in fine intergrowths with hexagonal pyrrhotite. Lenticular lamellas of troilite are disposed in such a manner that they are subparallel to the basal parting of pyrrhotite I. The lamellas of troilite increase in number and size in the periphery of the grains and along their cracks. Slender borders and irregularly shaped vermiform agglomerations of troilite are also found in pyrrhotite II.

The distinctive characteristic of troilite-pyrrhotite ores is the greater abundance of cubanite in them. Cubanite occurs in these ores not only in the form of lamellar inclusions in chalcopyrite, but also as granular aggregates forming veinlets that intersect pyrrhotite, chalcopyrite and pentlandite. As the content of granular cubanite increases, the troilite-pyrrhotite ores gradually alter to the troilite-cubanite-pyrrhotite ore variety.

Chalcopyrite (talnakhite, mooihoekite and chalcopyrite proper) ores. Among the chalcopyrite ores there have been distinguished three main mineral varieties with one of the minerals of the chalcopyrite group predominating in each of these varieties.

Two of them (talnakhite and mooihoekite ores) are unique varieties unknown so far at any of the other deposits in the p.151 world. Sulphur-poor minerals of the chalcopyrite group (talnakhite, mooihoekite and two cubic chalcopyrites, which differ in composition, but are similar in the size of their cubic primitive unit cell) predominate in the composition of these ores.

The third variety is represented by the chalcopyrite ores proper with stoichiometric tetragonal chalcopyrite as their essential mineral. Tetragonal chalcopyrite is also present as an accessory mineral in talnakhite and mooihoekite ores, but the ores composed of tetragonal chalcopyrite commonly occur separately from talnakhite and mooihoekite ores. They are localized amidst the pyrrhotite variety of ores, mainly at the base and in the flanges of ore deposits, or form discrete slender veins.

Talnakhite ores may occur together with mooihoekite ores, as well as separately from them. For example, at the Talnakh deposits there have been recorded only talnakhite ores. At the Oktyabr'skii deposit mooihoekite ores predominate, but talnakhite ores occur together with them.

Talnakhite and cubanite-talnakhite ores. A characteristic external feature of these ores is their rapid oxidation, as a result of which a variegated film of tarnish appears within hours in their fresh shears exposed to the air. Large spherical agglomerations of pentlandite (1-2mm to 2-3cm) stand out on the oxidized surface of polished lumps of ore against the background of variegated aggregates of talnakhite, as a result of which the ore acquires a porphyritic aspect. A meshwork of light-coloured, variously oriented lamellas and veinlets of cubanite, which is considerably less susceptible to oxidation, is readily observable on the oxidized exterior of cubanite-talnakhite ore samples (Plate XXI,a).

The mineral composition of these ores varies, but their principal minerals are limited in number, as is also the case with the other major mineral varieties of ores. There are only three principal minerals in these ores: talnakhite attaining a content of 60-65%, pentlandite (15-20%) and cubanite (5-25%). Magnetite is the accessory mineral invariably present in the ores (5-7%). Galena, sphalerite, silver and electrum are found in them often, but rarely form large agglomerations; compositionally diverse minerals of the platinum group elements are present in the form of small grains or intergrowths; some of the secondary sulphides (such as valleriite and mackinawite) are widely distributed; cuproan pentlandite, djerfisherite, shadlunite etc. are less common.

Talnakhite composes aggregates of hypidiomorphic, here and there twinned grains measuring 0.5 to 2mm. Some of them are homogeneous, while others contain minutest (2-3 um) regularly oriented lense-shaped or (depending on the section of the grains) spherical dot-like inclusions of tetragonal chalcopyrite. The orientation of the lamellar inclusions is different in each individual grain. They increase in size and number towards the periphery of the grains and towards the cracks, where there may be observed continuous borders of tetragonal chalcopyrite measuring a few hundredths of 1mm to 0.1mm in width.

In some places talnakhite contains minutest stellular crystals of sphalerite, which appear to have formed as a result of exsolution. Etching in aqua regia vapours brings out the twin structure of the talnakhite grains; moreover, individual twins are composed of aggregates of smaller (0.1 to 0.2mm) allotriomorphic grains.

Characteristic inclusions other than the lamellas of chalcopyrite, are larger (up to 0.02mm in width) lenticular crystals of pentlandite that also vary in orientation in different grains. Still larger (0.1=0.2mm to 2-3mm) vermiform veinlet-like agglomerations of pentlandite broken up by transverse cracks into blocks that may be displaced in relation to one another, cut across the boundaries of the talnakhite grains continuously extending from one grain into another.

Spherical porphyritic phenocrysts of pentlandite broken up by a meshwork of cracks, are intersected by veinlets of fine-grained talnakhite and cubanite and are surrounded by borders of the latter. Myrmekite-like intergrowths of pentlandite p.152 with talnakhite and cubanite have often been observed in peripheral loci of pentlandite agglomerations.

Cubanite is represented by two morphological varieties. Cubanite I forms lamellas measuring 0.5-0.1mm or larger tabular crystals (up to 0.2mm) with sharp lateral boundaries and split, less often straight blunt ends (Plate VIII,q). They do not project as a rule outside the individual talnakhite grains, and may adjoin in some places agglomerations of cubanite II. The latter is composed of granular aggregates (with grains measuring 0.1-0.3mm) which form veinlet-like agglomerations with very uneven boundaries (Plate VIII,b), or irregularly shaped loci in the aggregates of talnakhite. The content of cubanite II varies from isolated veinlets to 30%, in which case the ore is regarded as the cubanite-talnakhite variety.

Spherical or skeletal magnetite grains measuring up to 1mm, and sometimes intergrowths of several grains form inclusions in talnakhite and pentlandite. Concentrations of magnetite grains have been observed at the contacts of talnakhite grains.

Talnakhite ores owe their distinctive aspect to the secondary alterations of minerals. Talnakhite, cubanite and magnetite are often replaced by valleriite which forms veinlets in these minerals measuring up to 0.2mm in width, and pseudomorphs in magnetite grains with relict magnetite loci persisting here and there. Agglomerations of valleriite along the boundaries of the magnetite zones emphasize the zonal structure of some of the crystalline magnetite grains. Valleriite, together with mackinawite, replaces platy cubanite crystals. Pentlandite is readily replaced by mackinawite or cuproan pentlandite. Tabular, occasionally twinned mackinawite crystals measuring up to 0.5mm in width, replace porphyritic phenocrysts of pentlandite. Finely banded aggregates of mackinawite alternating with tetragonal chalcopyrite and cuproan pentlandite, develop in porphyritic pentlandite phenocrysts. Cuproan pentlandite forms a meshwork of extremely slender filamentous veinlets within pentlandite; these veinlets may grow denser changing to continuous loci that no longer contain relicts of pentlandite (Plate XI,a). Thin lenses of pentlandite enclosed in talnakhite may in some places be almost completely replaced by mackinawite.

Mooihoekite and cubanite-mooihoekite ores do not become oxidized in the air as rapidly as talnakhite ores and their tarnish is not as bright or as variegated as that of the latter ores. These ores resemble superficially bornite ores, particularly in weakly oxidized shears.

Similarly to talnakhite ores, the ores described have a massive or porphyritic texture. The latter develops on account of large spherical pentlandite agglomerations (up to 3-4cm in diameter) enclosed in compact, macroscopically homogeneous aggregates of mooihoekite. The texture of the ores is coarse-grained. Grains measuring up to 102cm.

The feature specific of these ores is that all the minerals of the chalcopyrite group occur in them in the form of close intergrowths: mooihoekite, both modifications of cubic chalcopyrite with a primitive unit cell, talnakhite and tetragonal chalcopyrite of a stoichiometric composition. The proportions of the constituent minerals vary widely, but the first three minerals invariably predominate. Talnakhite has been encountered less often and tetragonal chalcopyrite has been recorded only in intergrowths with talnakhite. Moreover, talnakhite predominates in some of the grains and tetragonal chalcopyrite predominates in others. The total content of all these minerals is 60% or more. Cubanite I and II (5-25%), pentlandite (15-20%) and magnetite (up to 10%) are constantly found in association with minerals of the chalcopyrite group.

Accessory and rare minerals are represented by galena, cadmium and manganesian sphalerite, by the series of minerals of platinum metals, by some rare minerals of selenium and tellurium, and by native silver. There have been recorded single finds of alabandite, a sulphide of manganese. Isolated agglomerations and veinlets of manganian shadlunite associated with late pentlandite have been encountered among the accessory minerals in addition to the widely distributed valleriite, mackinawite and cuproan pentlandite. p.153

Mooihoekite and cubic chalcopyrite have similar optical properties and can be distinguished only with the help of X-ray analyses. Microsamples for the X-ray analyses were taken under the microscope from the polished surface of the slide with the help of a slender steel needle. This enabled us to elucidate the internal structure of the grains. Abnormally anisotropic cubic chalcopyrite differs from the two preceding minerals because of its distinct bireflectance and by the bright pleochroic effects of anisotropy at crossed nicols.

The intergrowths formed by these minerals are very finely structured and vary in shape. Mooihoekite and cubic chalcopyrite are represented by isometric grains measuring 0.2 to 2.0mm, and by tabular crystals or lamellas (0.1-0.2mmXX1-2mm) that may form polysynthetic twins at an angle to the elongation of the lamellas (Plate VII,b). In some places the central part of the grain consists of mooihoekite, while its peripheral parts are composed of extremely thin polysynthetic twins of cubic chalcopyrite. Mooihoekite, which composes half the grain, may change to cubic chalcopyrite without any visible boundary. There has often been observed a multiple alternation of polysynthetic tabular mooihoekite twins with identical tabular crystals of cubic chalcopyrite (Plate VII,d). Both minerals enclose small grains (0.01-0.02mm) of abnormally anisotropic cubic chalcopyrite. The latter commonly composes aggregates of small (0.1mm or less) palmate grains, parallel lamellas and cuneiform aggregations alternating with mooihoekite and cubic chalcopyrite. There have also been observed monograins shaped in the form of lamellas

(0.1-0.2mm in width) with small insets of mooihoekite or cubic chalcopyrite.

Talnakhite has been encountered less often in intergrowths with mooihoekite and cubic chalcopyrite. Tabular crystals of talnakhite (0.1-0.3mmX1-2mm) with split ends alternate with identical or narrower lamellas of mooihoekite or cubic chalcopyrite.

It is obvious that such finely interpenetrated mineral aggregates (intergrowths) with this kind of mineral composition could have formed only as a result of unmixing of a solid solution undersaturated in sulphur, and of subsequent alterations of the phases to the subsolidus stage. This hypothesis is supported by the resemblance of the structures described to those resulting from unmixing of the solid solution of chalcopyrite obtained experimentally [174, 226, 241 and 269].

The particles (agglomerations) of pentlandite, cubanite and magnetite in these ores are similar in shape to those in talnakhite ores except for the size of the pentlandite agglomerations that are here larger than those found in talnakhite ores.

Cubanite-mooihoekite ores differ from mooihoekite ores in having a greater content of granular cubanite (up to 20-30%) forming veinlets and irregularly shaped agglomerations. As the concentration of cubanite rises, the ore gradually changes to the mooihoekite-cubanite variety.

Chalcopyrite ores proper. The principal ore mineral of these ores is tetragonal chalcopyrite with a stoichiometric composition (65-80%). Pentlandite (the content of which amounts to 10-50%) is represented by its modification with the highest content of nickel. Cubanite I and, less often, cubanite II (5-10%), magnetite (about 5%) and (in transitional varieties) pyrrhotite II, less often pyrrhotite I, are here accessory minerals. Among the rare minerals there have been encountered sphalerite, galena, some minerals of platinum, and argentopentlandite. Accessory minerals are here less abundant than in the other types of chalcopyrite ores, but are also represented by valleriite, mackinawite and late magnetite. The structure of the ore is massive and in the loci with spherical insets of pentlandite it is porphyritic (Plate XXI,b). The texture of the chalcopyrite aggregates is inequigranular with the grains measuring 0.5 to 2-3mm. Most of the chalcopyrite grains display complex twinning. Polysynthetic, lattice and basket-weave twins have been encountered most often. The products of unmixing of the solid solution found in chalcopyrite are minutest stellular crystals of sphalerite and lamellas of cubanite I differing in orientation from one chalcopyrite grain to another (Plate XIII,a). p.154

Porphyritic phenocrysts of pentlandite (measuring a few millimetres to 1.5cm) are spherical, but may sometimes be irregularly shaped. One of these agglomerations encloses chalcopyrite insets in the form of small intersecting lenses. Others may be intersected by veinlets of chalcopyrite. Slender (0.05mm or less) lenticular veinlets and skeletal grains of pentlandite have been encountered in chalcopyrite.

Magnetite occurs in pentlandite and chalcopyrite in the form of skeletal or spherical grains, and is found in the interspaces between the chalcopyrite grains in the form of dendritic agglomerations. Veinlets of a late fine-grained magnetite cut across chalcopyrite and pentlandite.

Granular cubanite occurs here and there in the form of irregularly shaped agglomerations amidst chalcopyrite aggregates and forms borders around the grains of pentlandite and magnetite. As the content of granular cubanite increases, the ore alters to the chalcopyrite-cubanite variety.

Pyrrhotite-chalcopyrite ores are transitional to pyrrhotite ores. Their content of pyrrhotite attains 25-30%. A characteristic feature of these ores is the abundance of fine-grained pyrrhotite II therein forming irregularly shaped concentrations and variously oriented veinlets. Pyrrhotite I is found here rarely and occurs only in the form of relict loci amidst chalcopyrite. In contrast to pyrrhotite ores, pentlandite forms here porphyritic phenocrysts (up to 5mm) and borders around the grains of magnetite.

Troilite-pyrrhotite-cubanite-chalcopyrite ores, in which chalcopyrite is the predominant constituent, are transitional between the pyrrhotite-chalcopyrite and chalcopyrite-pyrrhotite varieties on the one hand and cubanite ores on the other. In addition to the characteristic minerals of pyrrhotite-chalcopyrite ores, there appears here cubanite, as well as troilite that is constantly associated with cubanite. Large grains of pyrrhotite I have been observed only in the form of relict loci amidst chalcopyrite, as has also been the case in pyrrhotite-chalcopyrite ores. These grains invariably contain lamellar inclusions of troilite. A characteristic feature of the internal structure of these grains is the nearly total absence of lamellar pentlandite inclusions along their basal parting. Large lamellas of pentlandite have been encountered only in isolated grains of pyrrhotite.

The more widely distributed fine-grained pyrrhotite II also contains inclusions of troilite. It forms irregularly shaped concentrations and veinlets in chalcopyrite similar to those in pyrrhotite-chalcopyrite ores.

Cubanite is represented in these ores by regularly oriented platy inclusions in chalcopyrite, as well as by veinlets composed of granular aggregates. Lamellas of cubanite I may be replaced by finely granular pyrrhotite II. Sphalerite, galena, minerals of platinum and palladium, and argentopentlandite are found in these ores considerably more often than in pyrrhotite ores; accessory minerals are represented by mackinawite forming veinlets in chalcopyrite, pentlandite and cubanite.

Cubanite ores amalgamate a number of mineral varieties with a fairly large range of quantitative ratios of the principal ore-forming sulphides. This characteristic of their mineral composition is due to the intermediate position of cubanite ores in the ore deposits between all the principal varieties of ores described above. Cubanite ores are linked with these ore varieties by gradual transitions, which accounts for the presence of varieties transitional to pyrrhotite, talnakhite and mooihoekite ores, respectively, in addition to the cubanite ores proper.

Cubanite ores proper are distributed on a relatively limited scale. They are composed of cubanite, the content of which amounts to 60-70%, pentlandite (15-20%) and magnetite (5-10%) (Plate XXI,c). Minerals of the late associations, i.e. sphalerite, galena, minerals of the platinum group elements and some rare sulphides (djerfisherite and shadlunite), have been encountered in these ores in the form of isolated grains. Secondary minerals replacing the principal ore-forming sulphides, i.e. valleriite, mackinawite and cuproan pentlandite, are constantly present. Texture inequigranular. Cubanite grains p.155 vary in size from 0.5 to 5-7mm. Agglomerations of pentlandite vary in shape. Pentlandite forms porphyritic phenocrysts (measuring 1mm to 1cm) that are unevenly distributed amidst the aggregates of cubanite, and slender (0.1-0.2mm in width) lenticular or veinlet-like agglomerations, and may be present in the grains of cubanite in the form of minutest (0.02mm or less) crumbled acute-angled granules. Porphyritic phenocrysts and lenses of pentlandite are corroded and are intersected by cubanite veinlets branching off the cubanite aggregates surrounding pentlandite. Pentlandite may be replaced by mackinawite, here and there by cuproan pentlandite forming extremely fine meshworks of veinlets in pentlandite. Veinlets of valleriite cut across cubanite, pentlandite and magnetite.

Magnetite is distributed extremely unevenly in cubanite and forms concentrations of spherical, irregularly shaped or skeletal grains measuring hundredth fractions of 1mm to 1-2mm.

Troilite-pyrrhotite-cubanite and troilite-cubanite ores are ore varieties transitional to pyrrhotite ores. These ores differ from cubanite ores in that they contain hexagonal pyrrhotite that is finely intergrown with troilite, or troilite. Hexagonal pyrrhotite with lamellar inclusions of troilite that are subparallel to the basal parting of the grains, or troilite occur amidst the aggregates of cubanite in the form of islets varying in size and shape (Plate XXI,d). Gradual transitions of these ores to troilite-pyrrhotite ores, in which cubanite occurs only in the form of veinlets cutting across the chalcopyrite-pyrrhotite aggregates, undoubtedly testify to the relict nature of these islets persisting after the troilite-pyrrhotite or pyrrhotite ores become replaced by cubanite. In troilite-cubanite ores the ratios of cubanite and troilite vary within a large range (4:1 to 1:1). The ores with nearly equal proportions of these minerals have a knitted texture similar to that of large-grained pyrrhotite ores.

Knitted agglomerations of cubanite surround large (1-2cm) grains of troilite, similarly to tetragonal chalcopyrite in pyrrhotite ores. Troilite contains lamellar inclusions of pentlandite; moreover, at the boundary of troilite grains with cubanite there may be observed borders of pentlandite or platy intergrowths of cubanite with chalcopyrite. In the loci, where cubanite predominates, troilite occurs only in the form of relict islets (with grains measuring 1-2mm to 1cm) containing virtually no lamellas of pentlandite. The latter has been observed mainly in the form of porphyritic phenocrysts concentrated at the boundary of troilite with cubanite or within cubanite. Irregularly shaped agglomerations of chalcopyrite have been encountered in some places in these ores.

Chalcopyrite-cubanite ores differ from the cubanite variety of ores in that they contain varying quantities of tetragonal chalcopyrite. It is highly important to note that chalcopyrite is represented here mainly by its ferroan variety. Its agglomerations amidst the granular aggregates of cubanite are in the form of irregularly shaped inclusions with very uneven boundaries. The agglomerations vary in size from tenth fractions of 1mm to a few millimetres and are often intersected by veinlets of granular cubanite. The inclusions increase in size and number towards the contacts with the chalcopyrite ores, and in the latter there have only been recorded veinlets of granular cubanite cutting across chalcopyrite, here and there with lamellar inclusions of cubanite and pentlandite.

Talnakhite-cubanite, mooihoekite-cubanite, troilite-talnakhite-cubanite and troilite-mooihoekite-cubanite ores.

With regard to their mineral composition and spatial position these ores are transitional between the cubanite variety and the talnakhite and mooihoekite varieties of ores. The ores are similar with regard to the structure of cubanite aggregates and the form of agglomerations of their accessory minerals, but differ from one another in the composition of the relict inclusions in cubanite that are represented in some cases by talnakhite and in others by mooihoekite intergrown with other chalcopyrite group minerals. Cubanite replaces all the minerals of the chalcopyrite group, as well as pentlandite, which occurs p.156 in it in the form of inclusions. In addition to talnakhite and mooihoekite, there have been encountered in cubanite occasional relict islets of troilite. The maximum content of troilite in these ores does not exceed 5%.

Distribution of mineral varieties of ores and mineral zoning of the ore bodies.

The development of mineral zoning in massive ores is one of the most important characteristics of the process of ore formation at deposits of the Noril'sk province. The zoning manifests itself in the segregation of individual mineral varieties of ores in different parts of the ore deposits. The distribution of the zoned ore bodies within the horizon of massive ores produces zoning in the deposits.

However, mineral zoning is not characteristic of all the ore bodies. On the one hand there have been identified deposits with a simple structure that are composed mainly of pyrrhotite ores with non-uniformly distributed chalcopyrite, and on the other deposits with a complex structure comprising all the mineral varieties of ores.

Ore bodies with a simple structure composed of one (commonly pyrrhotite) variety of ores, are more common at most of the deposits of the Noril'sk region. Bodies of this kind have been detected at the deposits of the Noril'sk ore field

(Noril'sk I, Chernogorsk, etc.) and at the Imangdinskii ore field. Zoned bodies of massive ores have also been encountered at these deposits. Their mineral zoning manifests itself in that pyrrhotite ores are succeeded by the chalcopyrite ore variety with the development of intermediate chalcopyrite-pyrrhotite and pyrrhotite-chalcopyrite varieties of ores. Chalcopyrite becomes segregated mainly in the marginal parts of the ore bodies, often in the region of their pinchout.

N.S. Zontov [77] describes a highly interesting example of zoning in a complex body of massive ores from the Noril'sk I deposit. The ore body occurs at the endocontact of the intrusive massif and is a subhorizonal vein with an apophysis branching off vertically downwards. Its subhorizontal part is composed of pyrrhotite ores, while chalcopyrite ores concentrate in the vertical apophysis. At that deposit there have also been encountered chalcopyrite ores composing the apophyses oriented upwards from the main ore body. There have also been recorded bodies composed entirely of chalcopyrite ores without any visible link with the pyrrhotite ore variety.

At the Noril'sk I deposit there have been observed rare massive sulphide ore bodies displaying a more complex zoning with formation of cubanite-chalcopyrite and, less often, talnakhite and cubanite-talnakhite ores.

The most complete zonal distribution of mineral varieties of massive ores has been recorded at the deposits of the Talnakh ore field. Even though simple ore bodies are widely distributed at these occurrences, many of the deposits exhibit a clearly pronounced zonal structure.

Pyrrhotite ores predominate in the ore deposits with a simple structure; relatively thin fringes of chalcopyrite ores may develop in the contact-line locales. The zonal structure of the ore bodies manifests itself in these locales in the relative enrichment of the ores with chalcopyrite from the centre towards the flanges of the deposits. The mineral composition of the ores alters gradually and only on account of variations in the ratios of the two principal ore minerals, i.e. pyrrhotite and chalcopyrite, but without the appearance of new minerals or mineral associations. The succession of mineral varieties of ores forms a series of gradual transitions from the pyrrhotite to the chalcopyrite-pyrrhotite, pyrrhotite-chalcopyrite and chalcopyrite varieties of ores. Among the deposits with a complex composition the greatest diversity of mineral varieties of ores has been recorded in the deposit localized at the western flange of the ore field. This low-angle tabular body with a sublatitudinal strike is composed in its central part and southeastern flange of pyrrhotite ores. Only here and there at the base and, less often, in the locales adjoining the roof does the content of tetragonal chalcopyrite increase in these ores and they gradually change to the chalcopyrite-pyrrhotite or pyrrhotite-chalcopyrite varieties. Mooihoekite, talnakhite and cubanite ores concentrate in the northwestern flange, and some varieties of cubanite ores are localized in the eastern flange. Both these locales have a concentric zonal structure. The northwestern locale of the deposit has oval outlines in plan and is distinguished by a particularly complex structure (fig.28). p.157

The central part of that contour is composed of mooihoekite ores and of the less abundant talnakhite ore variety. It is surrounded by a zone of cubanite ores including all the transitional ore varieties: mooihoekite-cubanite, talnakhite-cubanite (in the northwestern part) and chalcopyrite-cubanite (in the south-east).

The next zone towards the periphery is represented by troilite-containing cubanite ores adjoining the talnakhite-cubanite and mooihoekite-cubanite ore varieties, while chalcopyrite-cubanite ores are succeeded by the troilite-pyrrhotite-cubanite-chalcopyrite variety. Lastly, the narrow outer zone bordering on pyrrhotite ores, is represented by troilite-pyrrhotite and troilite-chalcopyrite-pyrrhotite ores. The surrounding pyrrhotite ores are enriched in places in chalcopyrite and alter to chalcopyrite-pyrrhotite or even pyrrhotite-chalcopyrite ores. There have thus been observed in that locale the following successions of mineral varieties of ores (from the centre towards the periphery): 1.Mooihoekite → cubanite-mooihoekite → → mooihoekite-cubanite → troilite-cubanite → troilite-pyrrhotite → → pyrrhotite ores.

2.Mooihoekite → chalcopyrite-cubanite → troilite-pyrrhotite-cubanite-chalcopyrite → troilite-chalcopyrite-pyrrhotite → → pyrrhotite (chalcopyrite-pyrrhotite) ores.

3.Talnakhite → cubanite-talnakhite → talnakhite-cubanite → → troilite-cubanite (troilite-chalcopyrite-cubanite) → pyrrhotite ores.

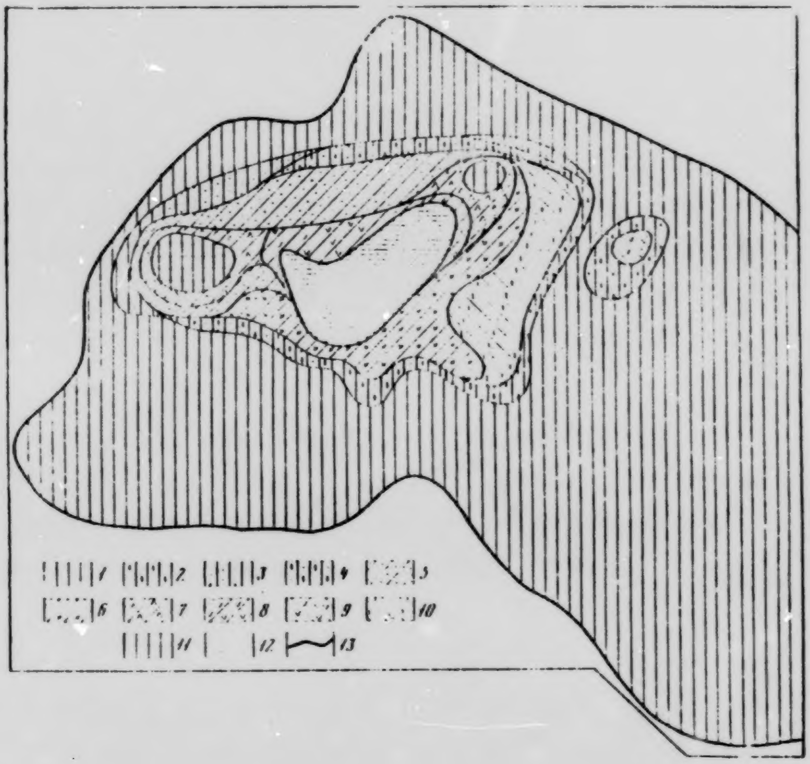
The structural feature specific of this locale is the constant presence of cubanite ores between the pyrrhotite (here and there chalcopyrite-pyrrhotite) and mooihoekite or talnakhite ore varieties, their gradual change to the one or the other variety. The zone transitional from cubanite to pyrrhotite ores is invariably composed of troilite-containing varieties of cubanite or pyrrhotite ores.

The talnakhite and mooihoekite ores containing the largest concentrations of copper, are localized in the vertical section (fig. 29) in the locales adjoining the roof and are succeeded towards the base of the deposit by mooihoekite- or talnakhite-containing cubanite ores, and still closer to the base by troilite-cubanite and troilite-pyrrhotite or chalcopyrite-troilite-pyrrhotite ores.

In the eastern flange of the Kharaelakh deposit there are no mooihoekite or talnakhite ores. Pyrrhotite ores are succeeded towards the eastern extremity of the deposit by chalcopyrite-troilite-pyrrhotite, cubanite-chalcopyrite-troilite-pyrrhotite and cubanite-chalcopyrite ores.

Another example of a deposit with a complex structure is an ore body localized in the south of the ore field. It is also a low-angle ore body with a submeridional trend. Unlike the deposit examined above, this ore body contains abundant pyrrhotite ores extending in the form of a narrow band along its southern, southeastern and northern flanges. Near the base the pyrrhotite ores are enriched in chalcopyrite and form transitions to the pyrrhotite-chalcopyrite and chalcopyrite ore varieties that are developed most extensively in the northern flange. Talnakhite ores predominate in the central part of the deposit, while chalcopyrite ores predominate in its northern flange. Cubanite ores are localized between the talnakhite (or p.159 chalcopyrite) and pyrrhotite ore varieties. In the sections, across the strike of the deposits and through their central part, pyrrhotite ores are succeeded from east to west by the troilite-pyrrhotite-cubanite, thereupon by the troilite-talnakhite-cubanite and cubanite-talnakhite varieties of ores. A similar succession of ore varieties can be traced in the northern flange except for the fact that talnakhite ores are replaced here by the chalcopyrite variety.

Fig. 28



Sketch plan of the distribution of mineral varieties in a deposit of massive ores.

(Fig. 28 continued)
1-Pyrrhotite ores; 2-Chalcopyrite-pyrrhotite ores; 3-Troilite-pyrrhotite ores; 4-Troilite-chalcopyrite-pyrrhotite ores; 5-Troilite-cubanite ores; 6-Chalcopyrite-cubanite ores; 7-Talnakhite-cubanite ores; 8-Mooihoekite-cubanite ores; 9-Pyrrhotite-chalcopyrite ores; 10-Troilite-pyrrhotite-chalcopyrite-cubanite ores; 11-Talnakhite and cubanite-talnakhite ores; 12-Mooihoekite and cubanite-mooihoekite ores; 13-Contours of the ore body.

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Talnakhite or chalcopyrite ores are localized in the vertical section in the roof-line locales and are succeeded towards the base of the deposit by cubanite and troilite-cubanite ores. The zone of cubanite ores is represented by the troilite-cubanite, troilite-talnakhite-cubanite and talnakhite-cubanite ore varieties alternating repeatedly along the vertical.

Cubanite ores thus occupy in this deposit a position intermediate between the pyrrhotite and talnakhite or chalcopyrite ore varieties.

In addition to the ore bodies examined there have been detected zoned deposits in the eastern and northern parts of the ore field recapitulating almost exactly the patterns of distribution of mineral varieties of ores described above. Most of the complex ore bodies are confined to the flanges of the ore field, whereas deposits with a simple structure are localized for the most part at a distance from the flanges of the tract. Mineral zoning is commonly observed in the parts of the ore bodies localized in the endocontact of stratified massifs. Talnakhite and mooihoekite ores occur in the zoning described exclusively amidst intrusive rocks; cubanite ores are confined to the parts of the deposits projecting into the rocks of sedimentary-metamorphic beds; and pyrrhotite ores almost always compose the parts of the deposits occurring amidst metamorphosed sediments.

Fig. 29

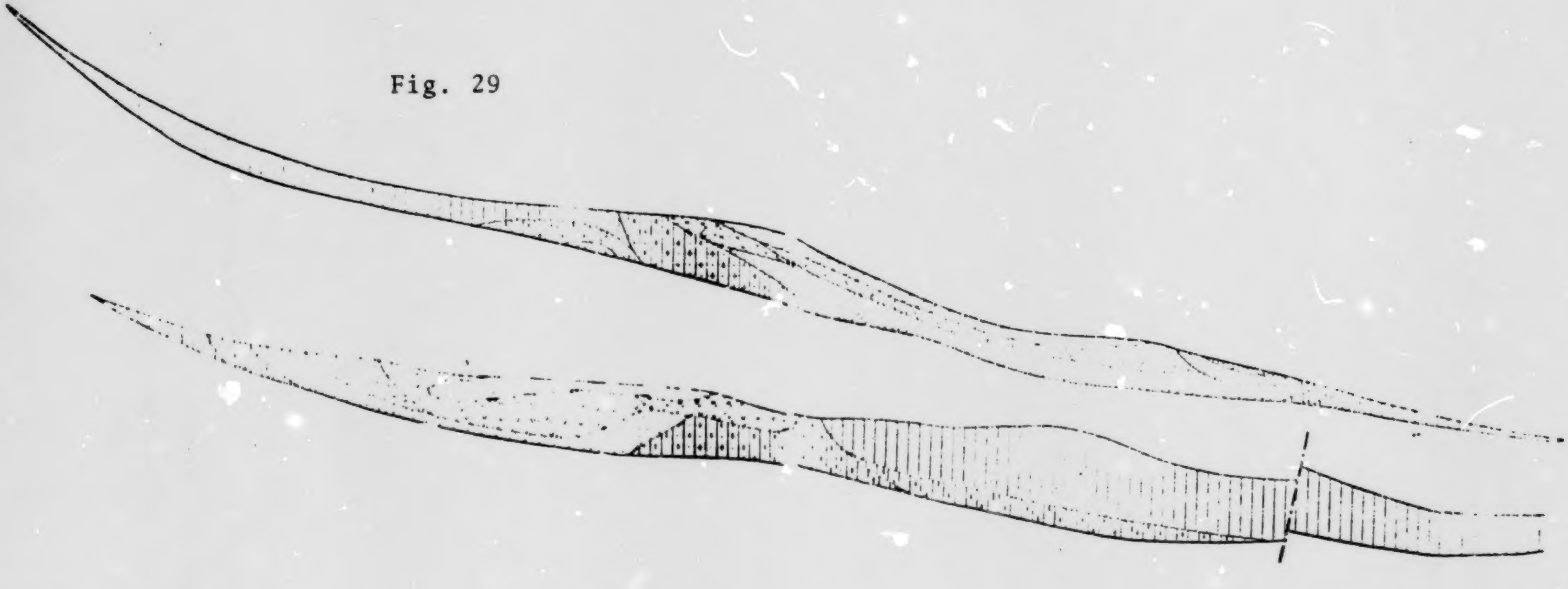

Fig. 29
Distribution of mineral varieties in sections of a deposit of massive ores.

Same legend as in fig. 29.

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The distribution patterns of different ore varieties examined above suggest that the mineral zoning of massive sulphide bodies [56] is of two types. The first type consists of a number of transitions from pyrrhotite to chalcopyrite ores, and the second type of those from pyrrhotite to cubanite and mooihoekite or talnakhite ores. The two types of zoning differ not only with regard to the variations in the composition of the mineral associations, and to the proportions of the ore-forming sulphides, but also in the patterns of accumulation of the ore-forming components [56].

CRYPTIC ZONING OF ORE BODIES

Zonal structure of ore bodies manifests itself not only in the distribution of mineral varieties of ores, but also in systematic variations in the composition of the principal ore p.160 minerals.

The patterns of variations in the composition of the pyrrhotite and pentlandite group minerals have been studied on the example of the ore deposit with the greatest diversity of mineral varieties of ores.

Pyrrhotite ores from that deposit contain hexagonal pyrrhotite of a variable composition, as well as monoclinic pyrrhotite, intergrowths of the two with varying phase ratios, intergrowths of hexagonal pyrrhotite with troilite, and troilite. Hexagonal pyrrhotite and its intergrowths with monoclinic pyrrhotite predominate. Troilite and its intergrowths with hexagonal pyrrhotite have been observed only in isolated loci, in the zone of troilite-pyrrhotite and troilite-cubanite ores. Homogeneous monoclinic pyrrhotite has been encountered in lesser quantities and is confined predominantly to the northeastern part of the deposit located in the submeridional tectonic zone.

Variations in the composition of pyrrhotite. Monoclinic pyrrhotite with the highest contents of sulphur or its intergrowths with hexagonal pyrrhotite are located in the vertical section mainly near the roof of the deposit. The relative content of monoclinic pyrrhotite gradually decreases towards the flat wall of the deposit until it disappears completely. At the same time the composition of hexagonal pyrrhotite also alters. There is record of the following examples of the distribution of monoclinic and hexagonal pyrrhotite from the roof towards the base of the deposits (fig. 30).

1. Monoclinic pyrrhotite in the roof, intergrowths of monoclinic and hexagonal pyrrhotite in the central part, and hexagonal pyrrhotite at the base. The d_{102} values of hexagonal pyrrhotite in its intergrowths with the monoclinic variety are stable throughout the interval (2.0673Å, which corresponds to the 47.45 at.% content of metal), but rise in the locale composed of homogeneous hexagonal pyrrhotite (to 2.0714Å, content of metal 47.80 at.%). In other instances the absolute values of d_{102} may be higher or lower than its value in the example discussed, but the relative value of d_{102} increases with transition to homogeneous hexagonal pyrrhotite in all the instances examined.

2. Intergrowths of monoclinic and hexagonal pyrrhotite are found throughout the section with the content of monoclinic pyrrhotite decreasing gradually from the roof towards the base of the deposit; d_{102} of hexagonal pyrrhotite rises gradually from 2.0673 to 2.0700Å as the relative content of monoclinic pyrrhotite decreases.

3. Intergrowths of hexagonal and monoclinic pyrrhotite occur in the roof and hexagonal pyrrhotite is found at the base; in the locales with the intergrowths the d_{102} of hexagonal pyrrhotite varies slightly: from 2.0673Å (47.45 at.% Me at the monoclinic to hexagonal pyrrhotite ratio equal to 1:2) to 2.0681 (47.50 at.% Me at the content of monoclinic pyrrhotite of about 15%); in the loci composed of hexagonal pyrrhotite alone, d_{102} noticeably increases: from 2.0707 (47.75 at.% Me) to 2.0734Å (48 at.% Me).

4. Only hexagonal pyrrhotite occurs throughout the section. In some cases d_{102} fairly smoothly increases from 2.0714Å (47.80 at.% Me) to 2.0732Å (48.0 at.% Me), while in others the values of d_{102} recur. Recurrence of the d_{102} values

has been observed in the ore intervals separated by interlayers of ore-free rock (gangue). For example, in one of the traverses of the ore body d_{102} increases from the roof to the base from 2.0620Å to 2.0670Å (47.00-47.40 at.% Me), and once again from 2.620Å to 2.0660Å (47.00-47.30 at.% Me); in another traverse from the roof-line part of the deposit the values of d_{102} change from 2.0721Å to 2.0748Å (47.80-48.20 at. % Me) and in the centre from 2.0734 to 2.0769Å (48.00-48.25 at.% Me).

It is thus evident that in all the examples discussed the concentration of iron in pyrrhotite distinctly increases from the roof towards the base of the deposit. This increase is manifest not only in that monoclinic pyrrhotite with the highest sulphur concentration is succeeded by hexagonal pyrrhotite with a higher iron content, but also in the rise of the iron concentration in the hexagonal pyrrhotite. This pattern is somewhat more complex in the locales of the deposit including interlayers of ore-free rocks. In such instances the concentration of iron in pyrrhotite increases from the base towards the roof; moreover, the closer the ore interval is to the base, the greater the iron content in its pyrrhotite. p.161

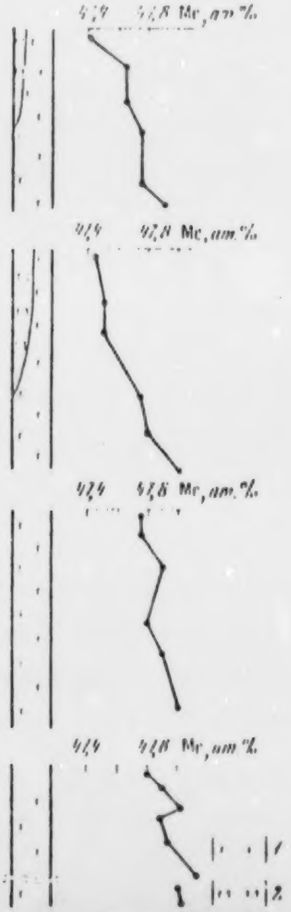
The pattern of variations in the composition of pyrrhotite within the deposit as such is less clear. Locales of relatively iron-rich pyrrhotites have been encountered fairly close to those of pyrrhotites with lower iron concentrations.

The most clearly defined phenomenon is the increase in the content of iron in pyrrhotite towards the contacts with cubanite ores, where the values of d_{102} change from 2.0700Å to 2.0769Å (47.65-48.25 at.% Me), whereas in locales remote from these contacts the d_{102} values change from 2.0620 to 2.0714Å (47.00-47.8 at.% Me).

The varieties of hexagonal pyrrhotite with the highest contents of iron have been encountered in troilite-pyrrhotite and troilite-pyrrhotite-cubanite ores, where hexagonal pyrrhotite occurs in intergrowths with troilite and d_{102} is 2.0714-2.0775Å (47.80 to 48.40 at.% Me).

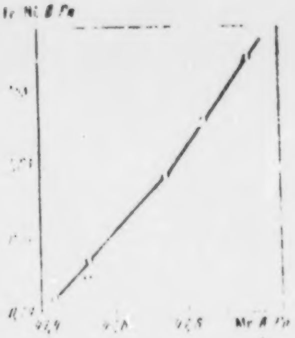
Variations in the composition of pentlandite. Variations in the contents of Ni and Fe in pentlandite are closely related to the succession of mineral associations or mineral varieties of ores. The concentration of nickel in pentlandite from pyrrhotite ores varies very little (Fe:Ni is 0.76 to 0.86; fig. 31). Pentlandites with the highest concentrations of nickel (Fe:Ni=0.76) associate with monoclinic pyrrhotite. In the associations comprising intergrowths of monoclinic and hexagonal pyrrhotites (the Fe content in hexagonal pyrrhotite is 47.4-47.8 at.% Me) the content of nickel in pentlandite drops, i.e. Fe:Ni changes from 0.78 to 0.84. The pentlandite associated with homogeneous hexagonal pyrrhotite (Fe varying from 47.8 to 48.0) has an even lower nickel concentration (Fe:Ni=0.83-0.86). As pyrrhotite ores alter to the chalcopyrite-pyrrhotite ore variety and eventually to chalcopyrite ores, the content of nickel in pentlandite rises (Fe:Ni=1 to 0.8). The pentlandites found in association with tetragonal chalcopyrite (in chalcopyrite ores) have the highest Ni contents (Fe:Ni up to 0.6).

Fig. 30



Variations in the content of iron in hexagonal pyrrhotite in the vertical section of a deposit of massive ores.

Fig. 31



Distribution of nickel in pyrrhotite and pentlandite coexisting in massive ores.

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In ore deposits with a complex structure the concentration of nickel declines (Fe:Ni varying from 1.03 to 1.63) as pyrrhotite ores give way to the troilite-pyrrhotite → cubanite → mooihoekite (or talnakhite) varieties. In this succession of ore varieties the highest nickel concentrations are found in pentlandite from troilite-pyrrhotite ores (the troilite|hexagonal pyrrhotite| pentlandite Fe:Ni=1 association), intermediate nickel contents (Fe:Ni=1.3) in pentlandites from cubanite ores, and the lowest concentrations of nickel (Fe:Ni=1.63) in talnakhite and mooihoekite ores. p.162

VEINLET-IMPREGNATED AND BRECCIOID* ORES

The ores localized in the exocontacts of intrusive massifs are of two types: veinlet-impregnated and brecciated ores. The common features of these ores are that they are confined to compositionally identical metamorphic and metasomatic rocks and display a somewhat similar spatial distribution of constituent mineral varieties, as well as a certain similarity in the nature of mineral intergrowths and in the ratios of sulphides and silicates. The differences between these ores are as follows. First of all the concentration of sulphides is considerably higher in brecciated ores: it averages 25-30% and may attain 60-80% in isolated in locales, which brings brecciated ores closer to massive ores. There have also been recorded instances where ores with a brecciated structure go over directly into veins or veinlets of massive ores with a massive structure. Mineral aggregates also differ markedly in morphology: their mineral composition is generally simpler in brecciated than in veinlet-impregnated ores. The structure of mineral aggregates, the types of intergrowths and the composition of ore minerals have a number of characteristics accounting for a certain degree of similarity between brecciated and massive ores.

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*Brecciated. Translator.

It may thus be concluded that brecciated ores are in some ways intermediate between the veinlet-impregnated exocontact ores on the one hand and massive ores on the other. In further descriptions it is therefore advisable to treat the veinlet-impregnated ores separately from brecciated ores. It should be noted that the designation "brecciated ores" is a collective term, since it characterizes the structural aspect of the most widely distributed ore variety. In addition to that variety, there have been recorded abundant ores with impregnated, veinlet-impregnated or densely impregnated (up to 80% sulphides) structures, as well as ores with a massive structure (massive ores). All these varieties of ores alternate in space in a systematic manner without cutting across one another, which permits us to regard them as products of the same process.

STRUCTURAL AND TEXTURAL CHARACTERISTICS OF VEINLET-IMPREGNATED ORES

These ores are characterized by a multitude of structural patterns, a complex mineral composition and a large number of mineral associations. The distribution of the ore-forming sulphides determining the structural aspect of the ores, is controlled by the structures, textures and physico-mechanical properties of their metamorphic or metasomatic host rocks. The ores are localized for the most part in pyroxene, anhydrite-pyroxene, forsterite, forsterite-spinel and feldspar-pyroxene hornfels, in calcareous or magnesian metasomatic rocks, and in serpentinite or, less often, brucite rocks. The sulphides are disposed along the bedding or schistosity planes of the rocks, penetrate into the rocks along the cracks or fill the interstices between the grains of pyroxene, forsterite, serpentinite (which replaces forsterite), brucite and other silicates. As a result of this there arise various banded (Plate XXII,a), veinlet-impregnated (Plate XXII,b) or impregnated structures. The proportion of sulphides in the rocks varies widely ranging from a sparsely dispersed impregnation to a dense "saturation" or an almost complete substitution of sulphides for the rock (Plate XXII,c).

Banded ore structures arise on account of the alternation of bands varying in thickness. Some of these bands have high contents of sulphides, while others contain no sulphides at all. In finely banded structures the bands of sulphides measuring 2-3mm in thickness with the sulphides filling the interstices between the grains of pyroxenes, are separated by anhydrite-pyroxene bands 3-5mm in thickness. In the event of a high concentration of sulphides in the rocks, the fine-grained sulphide-silicate aggregates display only a weakly pronounced relict banded pattern. In the event of a non-uniform distribution of sulphides and in the presence of non-mineralized interlayers that are often composed of anhydrite, the ore has a coarsely banded aspect. Banded structures are characteristic of the ores localized in altered anhydrite-marlaceous rocks. The ores p.163 structures resulting from the mineralization of terrigenous sediments are commonly of the uniformly impregnated type and differ only with regard to their proportion of silicates and sulphides.

Veinlet or veinlet-impregnated structures are the most typical structural patterns of exocontact ores. Depending on the concentration and, particularly, distribution of sulphides in the rocks, there have been observed a)a sparsely disseminated impregnation of sulphides combined here and there with sulphide veinlets of a limited length (Plate XXII,b); b)isolated agglomerations of sulphides in the form of veinlets in non-mineralized rocks, and c)densely impregnated ores with a uniform or spotty distribution of ore minerals. The combinations of different structural patterns and the diversity of the intergrowths formed by sulphides with nonmetalliferous minerals, account for the great structural variety of the ores.

A characteristic feature in the structure of impregnated and veinlet-impregnated ores is the close interpenetration of ore-forming sulphides with various nonmetalliferous minerals of the host rocks. In the ores composed predominantly of pyrrhotite (the pyrrhotite variety), as well as in those, where chalcopyrite predominates (the chalcopyrite variety), the sulphides are disposed inbetween the grains of pyroxenes, forsterite, serpentine and brucite and form fine intergrowths with these minerals. In densely impregnated ores this leads to the formation of peculiar delicate lattice-like patterns produced by the combination of fine sulphide-silicate intergrowths and nonmetalliferous locales of the rocks. Recrystallization of silicates and increase in the size of their fabric units have been observed around the agglomerations of sulphides.

The size of sulphide particles is the characteristic determining the nature of the intergrowths formed by sulphides with nonmetalliferous minerals. In most of the sections and lumps of ores examined it varies from 0.02 to 0.12mm. There have also been encountered larger grains of ore minerals measuring up to 0.5mm or more; the thickness of individual veinlets and agglomerations varies from 1-2mm to 1-2cm attaining 10-15cm in the swells. Sulphide particles vary markedly in size even within the same section or lump of ore.

MINERAL ASSOCIATIONS OF VEINLET-IMPREGNATED ORES

Veinlet-impregnated ores have a varied and complex mineral composition. In these ores there have been identified close to forty minerals, which we can differentiate on the basis of their abundance into the principal (pyrrhotite, chalcopyrite, pentlandite, millerite, pyrite, valleriite and magnetite), accessory (bornite, chalcocite, marcasite, galena, sphalerite and nickeloan pyrite) and rare (clausthalite, galenoclausthalite, polydymite, djerfisherite, tochilinite, violarite, mackinawite, cubanite, hematite and perovskite) minerals. Minerals of the platinum, palladium, gold and silver group also belong to the group of rare minerals. The minerals listed above form a large number of mineral associations.

As a result of studies on the structural and textural characteristics, mineral composition and age relations of these minerals, there have been distinguished their primary and secondary associations.

The primary mineral associations are similar to a certain degree to the associations found in massive ores. They comprise chalcopyrite, pyrrhotite, pentlandite and a number of other, less common sulphides. The secondary mineral associations arise in the process of hydrothermal metamorphism of the ores and evolve by replacing minerals of the primary associations. The varying degrees of replacement account for the existence of gradual transitions from the ores, in which the primary associations predominate, to those composed predominantly of the secondary associations.

We have identified the following primary mineral associations in the ores: 1)pentlandite-chalcopyrite-pyrrhotite; 2)pentlandite-pyrrhotite-chalcopyrite; 3)pentlandite-chalcopyrite; 4)millerite-chalcopyrite; and 5)bornite-millerite-chalcopyrite.

All the above associations are fairly distinctly spaced out forming a regular succession of segregated loci in the ore bodies. p.164

The pentlandite-chalcopyrite-pyrrhotite association is one of the most widely distributed assemblages. The principal mineral of that association, i.e. pyrrhotite, amounts up to 70% of the total sulphides and is invariably represented by its monoclinic modification in contrast to what has been observed in massive and impregnated ores from intrusive rocks. By using the methods of magnetic powder patterns and X-ray diffraction and by determining the composition of pyrrhotite with the help of an electron-probe micro-analyser it has been established that the pyrrhotite found in the exocontact ores is represented by its monoclinic modification. Since analyses of the internal structure of this pyrrhotite failed to detect any phenomena suggesting that hexagonal pyrrhotite has been replaced here by the monoclinic pyrrhotite variety or relicts of the former, it may be inferred with confidence that the pyrrhotite arose primarily in the exocontact ores in the form of its monoclinic modification. Pyrrhotite in that type of ores is richer in nickel. Compared to the content of nickel in pyrrhotite from massive ores, this element varies widely in concentration (0.4-2.5 wt %). The content of nickel in pyrrhotite amounts for the most part to 0.8-1.1 wt %.

Fine-grained aggregates of pyrrhotite commonly fill the interstices between the grains of pyroxene and other silicates. Pentlandite forms minutest particles in pyrrhotite measuring hundredth fractions of 1mm (Plate XXIII,a). In larger sulphide aggregates pentlandite develops in the form of borders measuring 0.1-0.2mm in width, along the chalcopyrite-pyrrhotite boundary (Plate XXIII,b). Borders of pentlandite are found considerably less often in veinlet-impregnated ores than in massive ores composed of the pentlandite-chalcopyrite-pyrrhotite assemblage, and porphyritic phenocrysts of that mineral are extremely rare. The composition of pentlandite from the pentlandite-chalcopyrite-pyrrhotite association is not very variable (Ni---37.1-38.6; Fe---27.8-28.5; Co---0.6-1.25; and S---32.4-33.5 wt %). Similarly to pyrrhotite, it has a higher nickel content than that recorded in analogous associations from massive ores or from the ores impregnated in intrusive rocks.

In the forsterite and, particularly, periclase rocks altered to brucite metasomatites, chalcopyrite often occurs in subordinate quantities. Its concentration increases in pyroxene rocks, but amounts to 20-30% or less of their total sulphides. Chalcopyrite is represented by its common tetragonal modification. Its composition corresponds to the stoichiometric formula $CuFeS_2$. The content of nickel in chalcopyrite is almost two orders lower than its content in pyrrhotite and is commonly $\sim$ 0.01 wt %.

The pentlandite-pyrrhotite-chalcopyrite association differs from the preceding assemblage mainly because its predominant constituent is chalcopyrite. This association is less widely distributed than the pentlandite-chalcopyrite-pyrrhotite assemblage, but has been encountered here considerably more often than in massive ores. Pyrrhotite, which is also represented here by its monoclinic modification, occurs amidst chalcopyrite in the form of irregularly shaped agglomerations, which commonly contain no lamellar inclusions or flames of pentlandite. The contents of nickel in pyrrhotite are commensurate with those recorded in that mineral from the pentlandite-chalcopyrite-pyrrhotite association, but its concentrations in excess of 1 wt % are here more common.

Pentlandite forms isometric grains measuring 0.1-0.15mm, at the boundaries of pyrrhotite with chalcopyrite and of sulphide agglomerations with silicates. It differs in composition (Ni---38.0-40.6; Fe---25.5-28.2; Co---0.7-1.1, S-32.8 wt %) from pentlandite of the preceding assemblage because of its greater contents of nickel and lower iron concentrations.

The pentlandite-chalcopyrite association has fairly often been observed in the ores, but is found only in the loci of the ore bodies with a small thickness. Pentlandite forms isometric grains measuring 0.1-1.0mm, amidst chalcopyrite. With regard to its composition, this pentlandite is the richest in nickel (40.0-46.6 wt % Ni) of all the pentlandites found in different types of copper-nickel ores.

The millerite-chalcopyrite association (Plate XXII,c) is widely distributed in the ores composed predominantly of chalcopyrite. Isolated isometric grains enclosed in the chalcopyrite mass are here the typical form in which millerite occurs. There p.165 have also been observed aggregated of millerite grains localized in the interstices of silicates. The grains of millerite vary in size from 0.02 to 0.3mm.

The bornite-millerite-chalcopyrite association is represented less abundantly than the other assemblages. Fine intergrowths of bornite, millerite and chalcopyrite are characteristic of this association (Plate XXIII,d). It has been established that in the ores with banded structures bornite, millerite and chalcopyrite or intergrowths of two of these minerals may be confined to individual bands.

Isometric grains of pentlandite containing 42-45 wt % Ni, as well as small quantities of galena, sphalerite and chalcocite intergrown with bornite, have often been observed together with the minerals of this assemblage.

The characteristics of sulphide intergrowths in the millerite-chalcopyrite and bornite-millerite-chalcopyrite associations suggest that the constituents of these associations are primary minerals.

As was mentioned earlier, secondary mineral assemblages evolve as a result of the replacement of the early paragenetic sequences with formation of polymineral ores including newly formed pyrite, nickeloan pyrite, magnetite, millerite and minerals of the valleriite group, i.e. tochilinite, polydymite and djerfisherite, as well as relict minerals. The last two secondary minerals are less widely distributed, but are confined to definite ore varieties.

The main secondary mineral associations of veinlet-impregnated ores are the 1)pyrite-magnetite; 2)millerite-pyrite and polydymite-millerite-pyrite; 3)pyrite-valleriite and tochilinite-valleriite associations and 4)the association with djerfisherite.

Secondary associations develop as a result of the interaction of metamorphosing solutions with minerals of the primary assemblages. Numerous observations on the relations of the primary and secondary minerals have shown that pyrrhotite and, to a somewhat lesser degree, pentlandite undergo the most profound metamorphic alterations. When pyrrhotite breaks down, there commonly arise secondary pyrite and magnetite, sometimes marcasite. Nickeloan pyrite, millerite, polydymite or violarite, and sometimes vysotskite, a sulphide of nickel and palladium, evolve from pentlandite.

The relative stability of the primary associations millerite+ +chalcopyrite and millerite+bornite+chalcopyrite in the process of formation of the secondary assemblages, may be due to the development of analogous stable secondary associations with millerite and chalcopyrite during the replacement reactions. Only in rare cases has the newly formed stromeyerite+polydymite+ +valleriite association been observed to substitute for the bornite-millerite-chalcopyrite assemblage.

On the whole there have been distinguished two characteristic groups of reactions in the processes of replacement of primary associations by secondary assemblages: reactions with stable chalcopyrite and those with stable pentlandite. The relations of secondary associations with metasomatic facies are also quite definite. The pyrite-magnetite assemblage commonly occurs in relation with the development of the serpentine-hydrogrossular facies. The reactions resulting in formation of the valleriite associations with djerfisherite and magnetite are accompanied by the development of brucite and brucite-serpentine-chlorite rocks replacing forsterite-spinel and periclase hornfels and marbles.

The magnetite-pyrite association is the most widely distributed and most typical product of alteration of the pentlandite-chalcopyrite-pyrrhotite assemblage. Different stages of replacement have been observed in the ores. Pyrrhotite may be replaced completely without leaving any relicts, in which case there arise in its place fine intergrowths of magnetite, pyrite and marcasite. Nickeloan pyrite forms larger zonal metacrysts amidst these intergrowths. Individual zones of that pyrite are enriched in nickel (up to 2.9 wt %) or cobalt (up to 0.13 wt %), respectively, while the contents of these minerals in the fine-grained pyrite are 0.1 wt % or less. Magnetite composes slender lenticular parallel veinlets arranged along the basal parting of the former pyrrhotite grains. p.166

Chalcopyrite and pentlandite may remain unchanged during the replacement of pyrrhotite, but may also contain veinlets of magnetite. Pentlandite does not survive intensive alterations of the ores, but its initial presence therein may be inferred from the shape of the millerite and polydymite particles forming pseudomorphs in pentlandite (Plate IX,1).

Secondary associations with pyrite also arise as a result of metamorphic alterations of the pentlandite-pyrrhotite-chalcopyrite association. Moreover, magnetite intergrown with crystalline grains of pyrite, with its xenomorphic grains and veinlets in chalcopyrite, is present only in subordinate quantities.

The millerite-pyrite association develops as a result of alterations of pentlandite-pyrrhotite-chalcopyrite and pentlandite-chalcopyrite ores. Pentlandite alters to an aggregate of nickeloan pyrite (with the content of nickel attaining 10.8 wt % and that of cobalt 1.9 wt %) and millerite; pyrrhotite becomes replaced by pyrite. Chalcopyrite undergoes no alterations and is found in intergrowths with pyrite as a relict mineral. As a result of the replacement of pentlandite in pentlandite-chalcopyrite ores there may evolve the nickeloan pyrite+polydymite (violarite) association (Plate IX,a).

The compositions of pyrite and nickeloan pyrite testify to the importance of the inherited chemistry of primary minerals in the formation of secondary mineral associations.

Associations with valleriite are fairly varied. They develop as a result of alterations of the associations, in which pyrrhotite predominates, as well as of those, where the predominant mineral is chalcopyrite.

Pentlandite is stable during the replacement of pyrrhotite ores by valleriite and persists in the valleriite aggregates replacing pyrrhotite. Magnetite and pyrite may form together with valleriite; the magnetite-valleriite and the pyrite-valleriite associations are widely distributed in the ores with secondary assemblages.

In chalcopyrite ores valleriite evolves mainly by replacing chalcopyrite. The relations of valleriite with the other minerals of secondary associations (valleriite veinlets cutting across all the ore minerals) evidence that valleriite is of a later origin.

Associations with djerfisherite are found rarely. A characteristic feature of this sulphide of potassium, iron, nickel and copper is that it is confined to the ores occurring amidst magnesium-rich brucite, spinel-forsterite or spinel-pyroxene-forsterite rocks.

Djerfisherite develops as a result of the interaction of autometamorphosing solutions with minerals of the pentlandite-chalcopyrite-pyrrhotite association. It commonly evolves by replacing pyrrhotite. Djerfisherite is often found in intergrowths with valleriite and is undoubtedly an earlier mineral than the latter, since valleriite often corrodes or intersects djerfisherite.

Djerfisherite occupies an intermediate position in the succession of ore mineral associations. The fact that it is confined to the locales, where secondary processes took place, and that it replaces the principal ore-forming sulphides permits us to refer djerfisherite to the secondary associations. Djerfisherite is, however, the earliest mineral in the succession of these associations.

MINERAL VARIETIES OF VEINLET-IMPREGNATED ORES AND ZONING OF ORE BODIES

Proceeding from the predominance of the principal ore minerals in veinlet-impregnated ores, these ores may be differentiated into five main mineral varieties and a number of transitional varieties comprising also significant amounts of other minerals (see Table 12). p.167

Pyrrhotite ores represented by the pentlandite-chalcopyrite-pyrrhotite association, are one of the widely distributed varieties of exocontact ores. They are particularly abundant in the ore bodies confined to the base of the intrusion and to deposits of massive ores. The contents of pyrrhotite in these ores are up to 60-80%, those of pentlandite 5-7% and of chalcopyrite 3-5 to 15-20%. In the horizons with impregnated or veinlet-impregnated mineral concentrations the content of chalcopyrite in some of the locales adjoining pyrrhotite-chalcopyrite or essentially chalcopyrite ores, may be 30-40% of the total sulphides. In such cases we distinguish the chalcopyrite-pyrrhotite ore variety similar in its mineral composition and character of its mineral intergrowths to pyrrhotite ores.

Pyrrhotite-chalcopyrite ores have been set apart as an independent variety on account of their extensive distribution in the bodies of exocontact ores, where they form fairly large tracts inbetween the pyrrhotite and chalcopyrite varieties of ore. Pyrrhotite-chalcopyrite ores are composed of minerals belonging to the pentlandite-pyrrhotite-chalcopyrite association. Their principal mineral is chalcopyrite (60-80%), while their content of pyrrhotite varies from 5-7 to 30-35% and that of pentlandite from 5 to 7%.

Chalcopyrite ores are fairly widely distributed, particularly in the horizons of exocontact mineralization in the roof of the intrusion. These ores have the most complex composition, since they comprise minerals of the pentlandite-chalcopyrite, millerite-chalcopyrite and bornite-millerite-chalcopyrite associations. Wherever these associations segregate forming sufficiently large separate locales within the ore bodies, we distinguish transitional pentlandite-chalcopyrite, millerite-chalcopyrite and bornite-millerite-chalcopyrite varieties of ores.

Pyrite ores are composed mainly of minerals from the secondary associations. These ores are fairly abundant in isolated parts of the ore bodies occurring in the lower exocontact of intrusive massifs. In addition to pyrite (the content of which may amount to 80% of the total sulphides), they contain magnetite and relict chalcopyrite, as well as nickeloan pyrite, millerite, polydymite and violarite. Superimposition of secondary associations on essentially chalcopyrite ores results in the development of the chalcopyrite-pyrite variety. If the original ores are of the pyrrhotite type, it leads to the formation of the magnetite-pyrite ore variety.

Valleriite ores evolve as a result of alterations of either pyrrhotite or chalcopyrite ores, in which valleriite forms as the latest mineral replacing chalcopyrite.

Distribution of mineral varieties of ores displays both vertical and horizonal zoning on account of the clearly defined zoning in the succession of their mineral paragenetic sequences. A zoning pattern with an identical succession of mineral associations [pentlandite+chalcopyrite+pyrrhotite →pentlandite+pyrrhotite+ +chalcopyrite →pentlandite+chalcopyrite →millerite (±bornite)+ +chalcopyrite] has been recorded in the ores localized under different conditions. Individual ore varieties may be lacking in some of the sections of these horizons. There may be observed a sharp transition from the pyrrhotite variety of ores to ores with a higher copper content, or the development of essentially pyrrhotite ores, while the other zones have a very limited thickness.

In the ore horizon localized in the roof of the intrusive body, there has been detected a definite relation between the zoning of mineral concentrations and the tectonic structures controlling the distribution of ores (metallotects). The pentlandite-chalcopyrite-pyrrhotite association is the only assemblage developed in the thickest eastern part of the ore horizon adjoining the zones of tectonic disturbances. Westwards from the tectonic zone the ore horizon decreases in thickness and the distribution pattern of the mineral associations alters. The pentlandite-pyrrhotite-chalcopyrite association appears in the composition of the horizon and is followed by the pentlandite-chalcopyrite assemblage; the bornite-millerite-chalcopyrite association is localized in the outermost part of the horizon. Distribution of the ores in zones has been observed in both p.168 vertical and horizontal sections of the ore body. The development of zoning in the distribution of mineral concentrations is accompanied by systematic changes in the composition of the principal ore-forming minerals. The content of nickel in pyrrhotite and pentlandite increases in a regular fashion. For example, in one of the sections of the ore horizon that is localized in the lower exocontact of the intrusion and is represented by the complete zonal sequence ranging from pyrrhotite to pentlandite-chalcopyrite ores, the concentrations of nickel in the pentlandites from pyrrhotite, pyrrhotite-chalcopyrite and pentlandite-chalcopyrite ores are 38.5, 40.6 and 46.6 wt %, respectively. As the concentration of nickel rises, the content of iron in the nickeliferous phases declines, which results in the appearance of millerite with 1 wt % or less of iron, instead of pentlandite in the outer zones of the ore body.

When secondary mineral associations develop on an areal scale, the structure of the ore bodies is significantly more complex. Pyrite ores are then particularly widely distributed and may take place of pyrrhotite ores in the zoning pattern examined. Valleriite ores occur, as a rule, more locally.

Horizons of impregnated and veinlet-impregnated ores in the lower exocontact of the intrusive massif commonly occur above the roof, as well as at the base of massive ore deposits. The distribution of different mineral varieties in these horizons also follows a complex zoning pattern. Essentially pyrrhotite impregnated and veinlet-impregnated ores are commonly localized above the deposits of massive ores and change in isolated loci to pyrite or valleriite ores. At the base of massive ore deposits there have been identified pyrrhotite-chalcopyrite and chalcopyrite exocontact ores succeeded towards the flanges by essentially pyrrhotite ores. In some locales of the ore field, amidst the ores occurring in the lower exocontact of massive ore deposits, there have been recorded fairly abundant veinlet-impregnated chalcocite-bornite ores with heazlewoodite and godlevskite.

The primary ores mentioned above from the lower exocontact of the intrusion are partly replaced by pyrite-magnetite-valleriite ores.

STRUCTURAL AND TEXTURAL CHARACTERISTICS OF BRECCIATED ORES

Brecciated ores proper are confined almost exclusively to metamorphosed sedimentary rocks. The mineral concentrations found in the apophyses of intrusive rocks occurring amidst brecciated ores, vary in intensity and are entirely of the impregnated type.

These ores display a variety of structures (listed in the order of the diminishing frequency of occurrence): brecciated, densely impregnated,banded and massive. These structures may be found separately or in various combinations with one another. The sulphide aggregates composing the ores therefore widely vary in size. As a rule they measure fractions of a millimetre to a few centimetres, but may increase in size to several metres in the locales of massive ores with a massive structure. In addition to the widely distributed brecciated ores with the sulphide cement particles inbetween the fragments measuring up to 2X2cm, there occur within individual intervals densely impregnated or impregnated ores that are represented by particles of sulphides measuring a few millimetres to a few microns. Lastly, a feature characteristic of these ores is that their specific structures develop regardless of the mineral variety composing the ores.

The ores with a brecciated structure are distributed most widely. The principal structural components of these ores are rock fragments cemented by sulphides; the sulphides
vary in content from 20 to 70% averaging 30-40%. The fragments* p.169
represented mainly by pyroxene hornfels, vary in shape and size. Round and oval fragments predominate, irregularly shaped fragments or fragments with bizarre outlines are found quite often, while acute-angled fragments with sharp boundaries are less common

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* The rock inclusions in the ores referred to as fragments, are in fact corroded relicts of rocks, which for the most part have not been displaced and have retained their original position. This circumstance distinguishes them from true fragments.

(Plate XXIV, a and b). The measurements of the fragments are even more variable ranging from tens of centimetres to a few fractions of a millimetre; moreover, the ores commonly contain both large (0.8-3.0cm) and small (0.5-5.0mm) fragments.

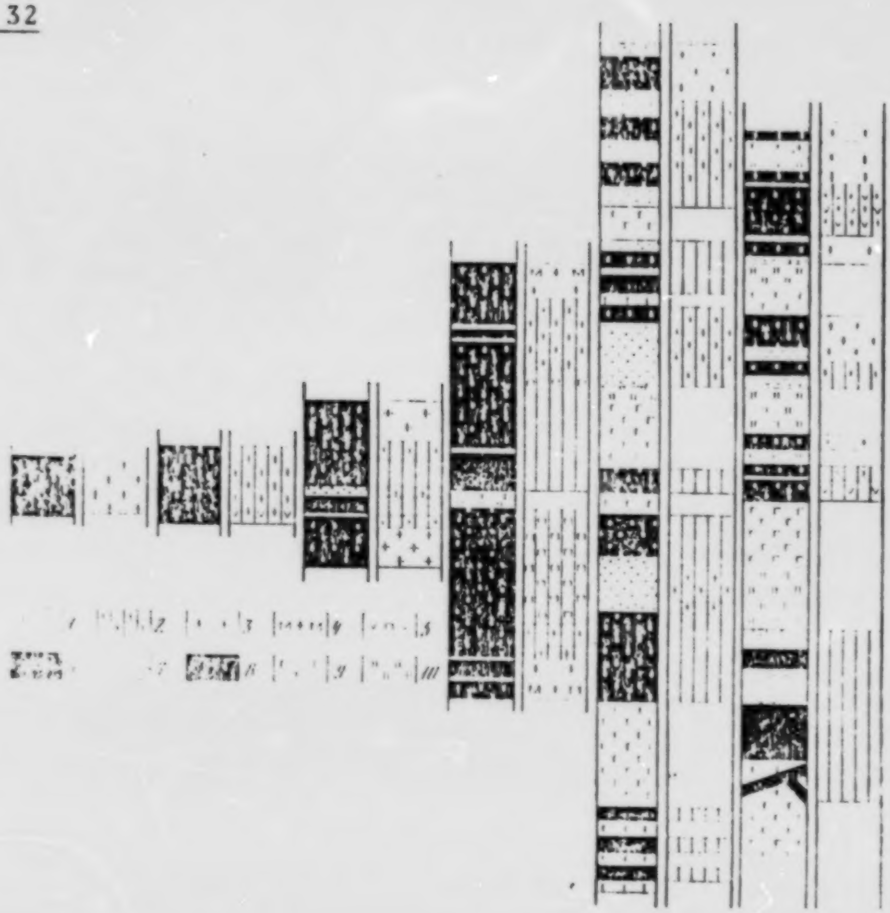
The proportions of silicates and sulphides vary widely in these fragments. Some of the fragments may be completely free of sulphides (Plate XXIV,b), while others contain rare, but fairly large (up to 5-7mm) sulphide inclusions that may be combined with particles of sulphides measured in microns. The sulphides together with carbonate and anhydrite fill the geodes and veinlets in the fragments.

There have often been encountered fragments composed in their peripheral part of finely intergrown sulphides and pyroxenes, but with the central portion containing only small inclusions or no sulphides at all. In the same samples isolated fragments may be composed entirely of a densely impregnated ore represented by a fine intergrowth of sulphides and pyroxenes with isolated spots of sulphide-free pyroxene aggregates.

The sulphide mass cementing the fragments may contain no silicate inclusions. There have, however, been often encountered brecciated ores with the cement composed of finely intergrown sulphides and pyroxenes. It is characteristic that the rock-forming minerals become recrystallized at the contact with sulphides, a phenomenon evident from that their particles grow larger than those of the minerals composing the rock.

Ores with densely impregnated structures are fairly widely distributed. They commonly occur inbetween the locales composed of brecciated ores, have been encountered at the base of these locales, and may be associated with locales of massive ores. Densely impregnated ores are composed of finely intergrown p.170
sulphides and pyroxenes and are similar in fabric to densely impregnated exocontact ores (Plate XXIV,c). The content of sulphides in these ores may attain 70%, but is commonly 30-50%.

Fig. 32



Main types of structures in the sections from the horizon of brecciated ores
1-5---Mineral varieties of ores: 1-pyrrhotite; 2-pyrrhotite-chalcopyrite; 3-chalcopyrite; 4-millerite-chalcopyrite; 5-valleriite and valleriite-pyrite; 6-8---Structural types of ores: 6-brecciated; 7-impregnated and veinlet-impregnated; 8-massive; 9-Horizons of the differentiated intrusion; 10-Contact-metamorphic and metasomatic rocks.

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Impregnated, banded and massive ore structures are considerably less wide-spread. Impregnated structures have been encountered in the locales of undisturbed pyroxene hornfels with rare agglomerations of sulphides. Low concentrations of impregnated ores have also been observed in microdolerites. Banded structures have been observed here and there. They are very similar to the banded structures of exocontact impregnated ores. Banded structures arise because of the alternation of parallel mineralized and non-mineralized bands in garnet-pyroxene rocks. Sulphides are represented in the mineralized bands by concentrations of insets or slender veinlets amidst aggregates of pyroxene. Garnet occurs in non-mineralized bands. Veins of massive sulphides with a massive structure have been observed in the section amidst both brecciated and densely impregnated ores.

Because of the complex structure of the section, the different structural ore types examined are invariably found in the horizon in various combinations and succeed one another in a variety of ways. The columns (fig. 32) constructed on the basis of borehold logs, show that against the background of generally predominant brecciated ores there occur locales composed of densely impregnated, impregnated, veinlet-impregnated or massive ores. In isolated sections the ore body may be composed entirely of brecciated ores, while in others densely impregnated and massive ores play a substantial role.

The structural-textural (fabric) characteristics of the ores and the proportions of metalliferous and nonmetalliferous minerals examined above evidence that the deposition of sulphides occurred by way of the superimposition of mineralization on a compositionally diverse complex of high-temperature metasomatic and metamorphic rocks, and that the formation of sulphides was accompanied in most instances by recrystallization of nonmetalliferous minerals.

MINERAL ASSOCIATIONS OF BRECCIATED ORES

Brecciated ores are composed of a relatively small number of ore minerals, among which pyrrhotite, chalcopyrite and pentlandite are the principal minerals, pyrite, millerite, magnetite and valleriite are accessory minerals and members of the platinum group (intermetallides, sulphides and tellurides), sphalerite, galena, arsenides of nickel, iron and cobalt, as well as djerfisherite and diaspore are rare minerals.

Brecciated ores are composed of fewer mineral associations than impregnated or veinlet-impregnated exocontact ores. These associations are differentiated into the primary and secondary assemblages.

We refer the 1)pentlandite-chalcopyrite, 2)pentlandite-pyrrhotite-chalcopyrite, 3)pentlandite-chalcopyrite and 4)millerite-chalcopyrite assemblages to the primary associations.

Fairly widely distributed secondary assemblages are the 1)magnetite-pyrite, 2)diaspore-vallerite and magnetite-diaspore-valleriite associations and 3)the association with djerfisherite. Secondary associations are represented much less abundantly in brecciated than in veinlet-impregnated ores.

The pentlandite-chalcopyrite-pyrrhotite association is the most widely distributed assemblage. Pyrrhotite, the predominant mineral of this association, is represented mainly by its monoclinic modification. Relicts of hexagonal pyrrhotite have been encountered occasionally amidst monoclinic pyrrhotite in the ores with brecciated or massive structures. Determinations of the nickel content in pyrrhotites of the pentlandite-chalcopyrite-pyrrhotite assemblage show that nickel concentrations vary in p.171 brecciated ores from 0.7 to 1.6 wt % averaging 1.1 wt %. The contents of nickel in pyrrhotite from massive ores with massive structures are considerably lower: 0.57-0.59 wt %. The concentrations of nickel established in pyrrhotite from the pentlandite-chalcopyrite-pyrrhotite association of densely impregnated ores are even lower (0.25-0.57%).

Pentlandite is represented, as a rule, by thin flames or lamellas confined to pyrrhotite. It has highly stable nickel contents (36.2-38.0 wt %). Pentlandite from ores with brecciated structures has higher nickel contents (37.2-38.0%). The contents of nickel in pentlandite from the locales of massive ores are somewhat lower (36.7-37.0%).

The intergrowths of the minerals from the pentlandite-chalcopyrite-pyrrhotite association have a distinctive character for each particular structural type. In the ores with a brecciated structure the sulphides cementing the fragments form aggregates of relatively large (up to 5-7mm) grains. Pyrrhotite invariably contains lamellas and flames of pentlandite (Plate VI,b) which are the most common fabric units of that mineral. The lamellas vary in thickness from 2 to 8 m and measure 30 to 150 m in length. Slender veinlet-like agglomerations or borders of pentlandite have been observed inbetween the variously oriented euhedral grains of pyrrhotite. There are no lamellas of pentlandite around such borders (Plate VI,b), which corroborates the theory that these lamellas formed as a result of unmixing of the pyrrhotite solid solution. The borders of pentlandite at the boundaries of pyrrhotite-chalcopyrite aggregates that are developed on a large scale in massive pyrrhotite ores, are considerably less wide-spread, thinner and commonly discontinuous in brecciated ores. Chalcopyrite forms isolated, sometimes fairly large (up to 5mm) insets in pyrrhotite, but occurs for the most part at the boundaries with nonmetalliferous minerals. In contrast to massive ores, knitted chalcopyrite formations fringing the grains of pyrrhotite, are found here rarely.

An interesting phenomenon observed in the ores with brecciated structures is the penetration of chalcopyrite inside the fragments on a larger scale. The bulk of pyrrhotite cements the fragments of pyroxene rocks, while a substantial portion of chalcopyrite forms inclusions within these fragments or borders around them, and, what is particularly important, fine intergrowths with recrystallized pyroxene grains inside the fragments. Pyrrhotite is found considerably less often in close intergrowths with pyroxene.

The ores with massive structures are identical to the sulphide ores from the large deposits at the base of the intrusion. Lamellas and flames of pentlandite occur in pyrrhotite grains measuring up to 1cm; chalcopyrite forms knitted agglomerations inbetween the grains of pyrrhotite; and pentlandite commonly develops in the form of borders along the pyrrhotite-chalcopyrite boundaries.

The pentlandite-pyrrhotite-chalcopyrite association is developed fairly extensively in the horizon of brecciated ores. Chalcopyrite predominates quantitatively among the minerals of this association, but its contents vary markedly (40-80%). The contents of nickel in the pyrrhotite from this assemblage are lower (0.57-0.74%) than those in the pyrrhotite from the pentlandite-chalcopyrite-pyrrhotite association, while the concentrations of nickel in pentlandite (36.6-37.9%) are the same in both mineral assemblages.

Pyrrhotite particles have a highly distinctive shape in chalcopyrite. Pyrrhotite commonly forms thin lamellas containing no inclusions of pentlandite. These lamellas are oriented in a variety of ways producing original textural patterns. The lamellas oriented at angles of 45 to 90° may be grouped into bands. These parallel bands line up in their turn forming rows oriented at angles of 60° (Plate XXIV,d). There have been observed reticulate textures, as well as randomly disposed lamellas in chalcopyrite.

Porphyritic phenocrysts measuring 0.5 to 5mm, are the typical form of pentlandite particles. The phenocrysts are randomly scattered amidst the pyrrhotite-chalcopyrite aggregates or adgrow to the fragments of the host rocks. p.172

In contrast to brecciated ores, the ores with massive structures contain pyrrhotite in the form of fine-grained veinlets in chalcopyrite.

The pentlandite-chalcopyrite association is less widely distributed in the ore horizon than the two preceding assemblages, but is found in many sections. Chalcopyrite predominates among the minerals of that association. It is represented by the usual tetragonal modification, as is also the case in its associations with pentlandite and pyrrhotite. The content of pentlandite amounts to 5-15%. In its composition there has been established 37.5 to 38.5%*, i.e. much less than in the pentlandite from a similar assemblage of veinlet-impregnated exocontact and massive ores. A feature characteristic of pentlandite is the random distribution of its porphyritic phenocrysts (measuring up to 5mm) amidst chalcopyrite.

Ores composed of the pentlandite-millerite-chalcopyrite or millerite-chalcopyrite association appear occasionally in the peripheral part of the ore horizon. Millerite is represented in these associations by veinlet-like agglomerations and xenomorphic-granular aggregates amidst chalcopyrite, as well as by borders around the fragments of pyroxene rocks. Porphyritic phenocrysts in chalcopyrite are the characteristic form of pentlandite particles. It has been established that the pentlandite from the pentlandite-millerite-chalcopyrite association contains 41.6% nickel, i.e. has the highest Ni concentration of all the pentlandites from the horizon of brecciated ores.

The pentlandite-millerite-chalcopyrite and millerite-chalcopyrite associations occur for the most part in brecciated ores.

As was mentioned earlier, secondary mineral associations are not extensively distributed in the horizon of brecciated ores. In contrast to the veinlet-impregnated exocontact ores, the locales of secondary assemblages in the horizon of brecciated ores are limited in size, discontinuous, and have a kind of geometry making it impossible to classify them as discrete bodies.

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* An obscurely worded sentence. Should it be 37.5 to 38.5% Ni? Translator.

The magnetite-pyrite association forms as a result of the replacement of pyrrhotite by the pentlandite-chalcopyrite-pyrrhotite assemblage. Pyrite develops at the boundaries of pyrrhotite and rock fragments, as well as inbetween the grains of pyrrhotite in the form of veinlets. In the event of an intensive replacement there arise fine intergrowths of pyrite and magnetite in place of pyrrhotite grains. When pyrite replaces the pentlandite-pyrrhotite-chalcopyrite association, it forms pseudomorphs in plastic grains of pyrrhotite. It has been established that pyrite from the magnetite-pyrite association contains 1.1%Ni and 0.8%Co. The magnetite-pyrite association is confined predominantly to brecciated ores.

The diaspore-valleriite assemblage has been encountered only in the horizon of brecciated ores and had not been previously recorded in any copper-nickel deposits. Diaspore [$HALO_2$] intergrown with valleriite or in the form of independent particles (up to 0.1mm) occurs in the sulphide cement around the fragments of pyroxene rocks or amidst the closely intergrown sulphide and pyroxene. Valleriite evolves by replacing chalcopyrite. The diaspore-valleriite association develops for the most part from the primary pentlandite-chalcopyrite-pyrrhotite or pentlandite-pyrrhotite-chalcopyrite association. Magnetite may be present together with diaspore and valleriite (Plate X,e). Djerfisherite associated with valleriite may also be present in these ores.

MINERAL VARIETIES OF BRECCIATED ORES AND THEIR DISTRIBUTION IN THE ORE HORIZON

Mineral varieties of brecciated ores are less varied than those of veinlet-impregnated or massive ores because of the smaller number of their constituent primary associations and limited development of their secondary assemblages. The main varieties of brecciated ores established on the basis of their pyrrhotite-chalcopyrite ratio are the pyrrhotite, pyrrhotite-chalcopyrite and chalcopyrite varieties. In addition to chalcopyrite and pyrrhotite, all these varieties contain pentlandite. Chalcopyrite ores with millerite form locales of p.173

a limited thickness and a limited areal extent.

Pyrrhotite ores are composed of pyrrhotite (60-80%), chalcopyrite (10-30%) and pentlandite (10-15%). Pyrite, magnetite and valleriite with diaspore may be present as accessory minerals. In some locales of the ore body their contents may be as high as 40, 20 and 30%, respectively. Galena, sphalerite and minerals of platinum (cooperite and sperrylite) have occasionally been observed in the ores.

Pyrrhotite ores are characterized by brecciated, densely impregnated and massive structures. With regard to their abundance, pyrrhotite ores predominate over all the other mineral varieties.

Pyrrhotite-chalcopyrite ores are also extensively developed in the ore horizon, but are less abundant than pyrrhotite ores. Pyrrhotite-chalcopyrite ores are composed of chalcopyrite (40-80%), pyrrhotite (10-40%) and pentlandite (10-15%). Their accessory minerals are pyrite, magnetite, valleriite and diaspore (in isolated loci these minerals may form larger concentrations, as is also the case in pyrrhotite ores), as well as sphalerite, galena and mackinwaite. Cubanite, djerfisherite, argentopentlandite and minerals of platinum (cooperite, michenerite and merenskyite) are among their rare minerals. Brecciated structures predominate in pyrrhotite-chalcopyrite ores.

Chalcopyrite ores are the least widely distributed variety in the ore horizon. There have been distinguished several transitional varieties among these ores: pentlandite-chalcopyrite ores containing traces of pyrrhotite (up to 5-10%), pentlandite-chalcopyrite and millerite-chalcopyrite ores. Chalcopyrite predominates in the ores (80-95%), while pentlandite amounts in them to 5-15%. Accessory minerals are represented by magnetite, pyrite, valleriite, sphalerite, galena, millerite and mackinawite, and minerals of noble metals by argentopentlandite, electrum, cooperite, stibiopalladinite, sperrylite, moncheite and kotulskite.

Combinations of different mineral varieties of brecciated ores in space account for the zoned structure of the horizon. There have been distinguished two main types of zoning: 1)Horizonal zoning determining the distribution of different ore varieties within the horizon as a whole, and 2)Vertical zoning characteristic of isolated sections in the horizon.

Different types of vertical zoning have been established in different locales of the horizon.

Horizontal zoning manifests itself mainly in that the chalcopyrite content increases in the ores towards the frontal region. The greatest abundance of chalcopyrite ores has also been recorded in the northern part of the horizon. Pyrrhotite and pyrrhotite-chalcopyrite ores predominate in its eastern and southern parts. In the other locales pyrrhotite and chalcopyrite ores are found in roughly equal proportions.

Vertical zoning of brecciated ores is more complex in character because of the differences in the contents and in the order of succession of different mineral varieties in different parts of the horizon. There have been distinguished several types of vertical structure in the horizon (see fig. 32).

1. Sections with a simple structure where one single mineral variety of ores develops within the confines of a traverse. Some drillholes may detect only chalcopyrite ores (I), others - chalcopyrite ores with minor quantities of pyrrhotite ores (II) or only pyrrhotite ores.

2. Sections with a symmetrical zonal structure where the mineral composition changes in a systematic manner from the centre towards the base and the roof of the ore horizon (fig. 32, III and IV). The succession of the mineral varieties is such that pyrrhotite ores develop in the centre, but give way to pyrrhotite-chalcopyrite ores both upwards and downwards in the section; thereupon the content of pyrite in the ores gradually declines and the ores alter to the chalcopyrite variety. Among the latter there have been distinguished pentlandite-chalcopyrite ores in the contact-line region and millerite-chalcopyrite ores

directly at the contact (IV). In some of the sections (III) the symmetrical zoning is incomplete, while in others (IV) p.174 is it complete. The zones vary in thickness. A characteristic feature of symmetrical zonal columns of this kind is the presence in their central parts of massive ores with a massive structure that are linked by gradual transitions to densely impregnated or brecciated ores.

3. Sections with a repeatedly recurring symmetric zonal pattern. The section is composed of a succession of alternating pyrrhotite and chalcopyrite ores. Sections with this type of zoning have been encountered most often in locales with extensively developed apophyses of the gabbro-dolerite massif (fig. 32,V,VI).

4. Sections with a simple zonal structure, where the mineral composition varies in one single direction, towards either the base or the roof of the horizon. Sections, in which chalcopyrite ores compose the upper part, while pyrrhotite ores are confined to the bottom portion, predominate. Reverse zoning has also been observed.

The distribution of secondary mineral associations does not follow a strictly regular pattern. Diaspore-valleriite and pyrrhotite ores have been encountered in different parts of the horizons, and can only be said to occur more often in the contact-line region of the ore bodies than elsewhere (fig. 32, V, VI). The area of distribution of secondary associations is commonly small, although in some drill-holes these associations may compose a significant part of the section (fig. 32,I and II).

CONDITIONS OF FORMATION OF COPPER-NICKEL ORES

Our discussion of the conditions under which the copper-nickel ores of the Noril'sk province formed, is based mainly on the new original evidence exposed in the preceding chapters of this work. The chief problems to focus on appear to be as follows: the geological factors involved in the formation and distribution of the ores; the composition, patterns of differentiation and conditions of crystallization of sulphide-bearing basaltic magmas; and the conditions under which large concentrations of massive and impregnated sulphides evolved in exo-contacts of the intrusions. It should be noted that these problems are not new and have been repeatedly raised and discussed in the literature. Many fundamental theories pertaining to the genesis of copper-nickel sulphide ores have been examined in the works of a fairly large group of researchers [45, 100, 222, 223, 249, 254, etc.]. However, the evidence obtained at each new stage of studies on these deposits made it possible to either elaborate in further detail the already existing notions, or to analyse new aspects of the problem in the light of freshly accumulated facts.

As is well known, the best developed concept of the genesis of copper-nickel ores rests on the notions of the magmatic nature of mineralization. The leading role of liquation differentiation processes of sulphide-silicate melts in situ [45] or in intermittent chambers prior to the ascent of magmas into the hypabyssal emplacement chambers, has been examined [99 and 100]. In attempting to apply this hypothesis in its pure form it proved difficult, however, to explain a number of specific aspects of mineralization, which prompted the researchers to search for new genetic models. The data on natural basaltic melts and the experimental studies that demonstrated the limited or low solubility of sulphur in mafic magmas, determined the direction of the search for an extramagmatic source of sulphur and gave rise to the hypothesis of the post-magmatic origin of ores [72 etc.]. The data of G. Kullerud and J. Naldrett on the sulphurization of basites as a possible explanation of the genesis of ores [72, 75 and 189], received a fairly wide application. It should be stressed that there is no agreement regarding the source of sulphur even in the concepts postulating the magmatic origin of ores. Some of them presume plutonic assimilation of crustal biogenic deposits [145], others - of crustal sulphates in the horizons in which the intrusions are localized [13, 51, 55, 44 and 45]. In assessing these models it should be noted that the theories allowing for an extramagmatic source of sulphur, cannot claim to provide a comprehensive explanation of the conditions under which the ores formed. Even if we accept the view that the decisive factor was the crustal assimilation of sulphur, the problem of the sources of the principal metals remains unsolved. Sedimentary beds must, of course, be ruled out as a source of metals. It is rather improbable that components such as nickel and, particularly, copper, noble metals or rare elements could form significant concentrations as a result of their redistribution from magmatic silicates.

Development of models of the postmagmatic genesis of ores touched upon an important problem in the theory of formation of magmatic deposits that has been relatively little studied, i.e. the problem of the role played by the fluidal (flow) phase. This problem is raised in a general way in the works by A.N. Zavaritskii and V.N. Lodochnikov, but has not been adequately studied after that, particularly with regard to copper-nickel ores. The only p.176 models in which the fluidal phase is regarded as the decisive factor in the deposition of ores, are those of the postmagmatic origin of ores. The data on metamorphic and metasomatic processes in association with intrusive traps do, indeed, testify that the fluidal phase forms significant concentrations in the sulphide-bearing basic melts. But the actual role of the fluids in the deposition of sulphides remains so far unclear.

GEOLOGICAL CONDITIONS OF THE LOCALIZATION OF COPPER-NICKEL ORES

Detailed analysis of the geological conditions under which the ores form is subject of special investigations, but is not our objective in this work and can therefore be touched upon only within the limits of the material presented earlier.

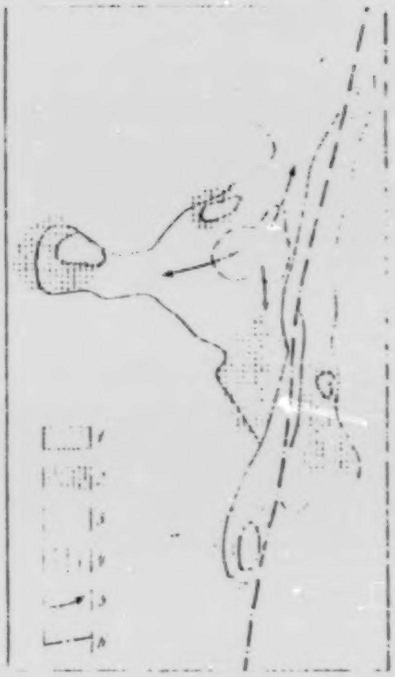
Data on the geological structure of deposits clearly evidence the unity of the geological-structural conditions under which definite types of intrusive trap massifs and sulphide-copper ores become emplaced. The distribution of these formations is controlled by plutonic tectonic structures, fault-line flexural folds and dislocations with plication forming apparently throughout the period of development of the troughs filled with explosive-extrusive rocks. As was mentioned earlier, most of the known stratified intrusions and of the copper-nickel ore occurrences associated with them, are grouped around submeridional tectonic structures and feather fractures diverging off them. It should be emphasized that the Noril'sk-Kharaelakh structure [9] is currently the most productive one, although there are geological and geophysical prerequisites for discovering other analogous tectonic structures in that region.

The main significance of the disjunctive structures and of the plicated structures accompanying them is that they are the principal tectonic elements determining the simultaneous presence of magmatic melts with different concentrations of sulphide components, in relatively small zones of the platform mantle. There has been observed a certain recurrence of the distribution patterns of different types of magmatic rocks in the ores bodies. The following instances of the co-existence of different types of intrusions have been identified. There may be observed associations of all the three types of sulphide-bearing massifs, i.e. of fully differentiated, differentiated leucocratic and differentiated melanocratic intrusions. In addition to that there have been encountered differentiated leucocratic and melanocratic intrusions occurring together. It is important to note that differentiated melanocratic intrusions are more extensively developed in the region examined than intrusions of the other two types. In the periphery of the ore district they are the principal magmatic formations in a number of tracts. One of the most important features of disjunctive structures is the duration of their tectonic activity. For example, at the Talnakh ore field pre-intrusive block faulting resulted in the occurrence of lithologically diverse Permo-Carboniferous deposits and Devonian beds at the same hypsometric level, as a consequence of which the horizon into which the intrusion was injected, has a highly varied petrographic composition. Postintrusive and postmineral movements resulted in formation of subsidence structures and in repeated displacements of the intrusion and of the ore horizons. Furthermore, there is evidence suggesting that tectonic movements were equally active in the period between the injection of the intrusion and deposition of the ores.

Premineral tectonic movements can be fixed most accurately at the Talnakh ore field in the locales adjoining the main suture of the Noril'sk-Kharaelakh fault. In that part of the intrusion there have been observed fractures with significant p.177 displacements of individual blocks. This is precisely the kind of dislocations resulting in the formation of cavities in the intrusive massif that are subsequently filled with massive sulphide ores. Premineral tectonic movements led to the formation of joint structures that contributed to the localization of massive and veinlet-impregnated ores in the upper exocontact zone of the intrusion. It is highly characteristic that mineral concentrations are confined in the upper exocontact to a relatively narrow band adjoining directly the main suture of the Noril'sk-Kharaelakh fault.

Plutonic tectonic zones thus appear to have acted as feeders of magmatic melts and as structures controlling the distribution of intrusive bodies and sulphide ores in the horizons of the platform mantle. Successive flows of different magmatic melts along the same structures account for the vertical "stacking" of different types of intrusive rocks that is characteristic of the ore fields in the Noril'sk region. Intrusive bodies represented by fully differentiated and differentiated leucocratic intrusive rocks occur in the upper part of the section in the ore field, while differentiated melanocratic massifs are localized in its bottom part. Moreover, the vertical distance between the different types of massifs may be quite small or the massifs may even be contiguous. If we assume that the melts were injected through high-angle magma feeders, then we can readily explain a number of specific features in the structure of the ore fields in that region. We can explain then, for example, the existence within the same intrusive massif of several locales with features of structure characteristic of the frontal flanges (zones) of the intrusion. This is particularly striking in the Noril'sk I and Talnakh massifs, where frontal zones have been recorded in the parts of the intrusions localized downdip of the trap troughs, as well as in those localized undip of these troughs. The intrusion rises then into higher stratigraphic horizons, basic differentiates increase in thickness relative to the thickness of ultrabasic differentiates, there appear ore-free picrites, etc. The general patterns of the distribution and zoning of mineral concentrations in the ore fields can be readily be explained. As is shown in fig. 33, the territory with the simplest structure of the ore zone is located in the central part of the Talnakh ore field, and locales with a complex structure are scattered in different directions from it. As is evident from the sketch map, zoned bodies with copper-rich talnakhite, mooihoekite and cubanite ores, as well as veinlet-impregnated and brecciated ores enriched in copper occur in the latter locales p.178 in the horizon of massive ores. This type of mineral zoning may apparently arise if the magmatic masses and ore-forming material move in the direction indicated by arrows in the drawing.

Fig. 33



Diagrammatic representation of massive and veinlet-impregnated copper-rich ores in the fully differentiated intrusion at Talnakh
1-Massive mooihoekite-talnakhite and chalcopyrite ores; 2-Veinlet-impregnated ores; 3-Massive pyrrhotite ores; 4-Presumed zone of localization of a magma feeder; 5-Presumed directions of the flow of magmatic melts; 6-The main suture of the Noril'sk-Kharaelakh fault.

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It is characteristic that the zoning of impregnated ores in intrusive rocks and the distribution of mineral associations in the horizons of picrite and taxite gabbro-dolerites also accord with that diagram.

Identical patterns of ore distribution have been recorded at the Noril'sk I intrusion. In the southern and southeastern flanges of that intrusion there have now been detected ore deposits similar to those found in the northern flange zone. There have been established veins of massive sulphides, mineral concentrations in olivine gabbro-dolerites, as well as veinlet-impregnated ores in the exocontact. It should be noted that the base of the intrusion rises sharply in that area from the stratigraphic level of terrigenous Permo-Carboniferous rocks into the horizons of basalts.

The proposed model is thus supported by examples of the two most thoroughly studied ore fields from the region.

Having broached the problems of the distribution and zoning of mineral concentrations in the ore fields, we arrive at the discussion of the role played by tectonic factors in the distribution of ores. Most deposits and veins of massive sulphides undoubtedly become localized under the same tectonic conditions as the sulphide-bearing intrusive massifs. The structures common for these formations are the subhorizonal zones forming as a result of block faulting in the marginal parts of the trap troughs. In addition to these zones there are structures that played an important part in the deposition of ores, but developed after the injection of stratified intrusions. The structures described earlier from the fault-line zone of the Talnakh ore field exemplify such formations. The distinctive aspects of the distribution of sulphide veins in the intrusion show that the stockwork zone could have formed only after the complete solidification (but not necessarily complete cooling) of the intrusion, since otherwise the large and long cavities could not have formed and the concordant displacements of rectangular blocks of magmatic rocks could not have taken place.

The other factors affecting the distribution of most bodies of massive sulphides are subhorizontal zones. Tectonic movements along these zones occurred not only at the time of the injection of the intrusion, but probably also during the period preceding the formation of massive ores. Construction of detailed sections shows that in the course of development of the ore bodies the endocontact zone of the intrusion is pushed apart.

It is equally important to distinguish the structural elements formed under the effect of the intrusions acting on the enclosing rocks. These are brecciation zones in the flanges of the intrusions, and locales of contact-line dislocations arising as a result of the mechanical activity of magmas [141]. Brecciated or veinlet-impregnated ores become localized in such locales.

The geological-structural elements controlling the structure of the ore fields and the distribution of ores in them have thus been identified: high-angle or subhorizontal tectonic zones and fault-line structures with lengthy periods of active development; and structural elements formed by the mechanical action of magmatic melts on the rocks of the sedimentary framework.

Analysis of the age relations of different structural elements and of the relations of intrusions and sulphide ores suggests that massive and veinlet-impregnated ores form later than the stratified massifs enclosing impregnated sulphides. p.179

DIFFERENTIATION AND CONDITIONS OF CRYSTALLIZATION OF MAGMATIC MELTS CONTAINING SULPHIDES

The facts that ores are constantly associated with definite types of intrusions, that the zonal structure of the intrusions is consistent with the distribution of ores in the ore fields, and that the processes of formation of sulphide and silicate mineral associations are interrelated, as well as other factors evidence that sulphide components participate in the magmatic process at all its stages, from the inception of the melts and their differentiation, and up to the consolidation of the magmas in hypabyssal chambers.

In order to clarify the conditions under which mineral concentrations form, it is therefore necessary to examine some characteristic aspects of formation of sulphide-bearing trap intrusions. In doing so, it is important to stress the following major features of these intrusions.

1. Among the great diversity of intrusive traps there have been identified three types of stratified intrusions containing sulphide ores. Each of these three types has its own specific features, composition and content of sulphides.

2. Sulphide-bearing intrusions or at least two of their types, i.e. fully differentiated and differentiated melanocratic intrusions, develop on a relatively limited scale in the trap province of the Siberian platform and are confined to the region marked by a highly specific extrusive magmatism with formation of ultrabasic lavas.

3. Stratified intrusions of all the types invariably occur together. The earliest types are differentiated leucocratic and fully differentiated intrusions, and the latest ones are differentiated melanocratic intrusions.

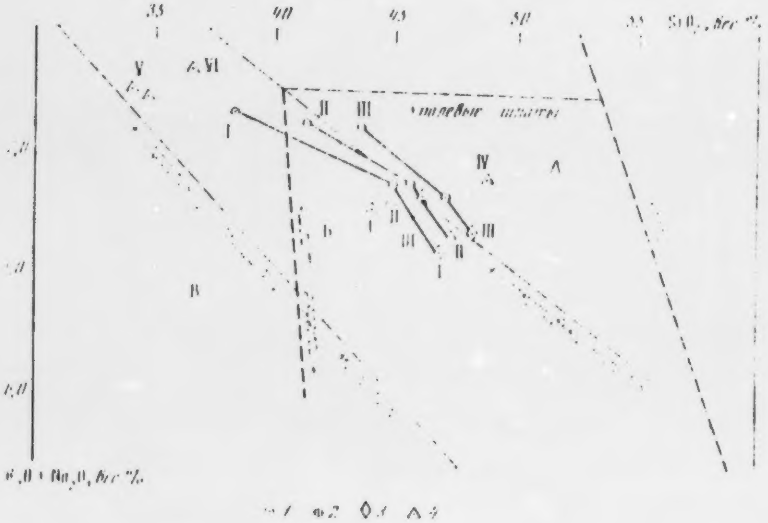
The data obtained from a great number of petrochemical analyses [9, 42, 64, 75, 147, etc.] are summarized in the diagram in fig. 34 [after 110]. These data enable us to identify a number of distinctive characteristics in the composition of the sulphide-bearing magmatic melts. The position of the points depicting average compositions of the intrusions and of their individual horizons shows that there are systematic differences between different types of massifs with different concentrations of sulphides. Undifferentiated intrusive traps correspond in composition to alkali-earth basites (fig. 34, field A, point IV). All the types of sulphide-bearing intrusives differ from these rocks in having somewhat higher alkalinity and basicity levels, and the points depicting their average composition lie at the boundary with the field of alkaline feldspathoid-free rocks or directly inside that field. A highly characteristic factor is the disposition of the points of average compositions in relation to one another and the arrangement of the lines interconnecting the points of the composition of different horizons in sulphide-bearing intrusions. The rocks of differentiated leucocratic intrusions correspond to alkali-earth rocks (fig. 34, point III), and the rocks of fully differentiated massifs have the highest alkalinity levels (fig. 34, point I). Compositions of the rocks of differentiated melanocratic intrusions occupy an intermediate position (fig. 34, point II). We wish to emphasize that these differences have been recorded in the average composition of the intrusions, as well as in the composition of the rocks from their individual horizons.

Comparison of the composition of ultrabasic horizons from these massifs is particularly indicative in that respect. Picrites from fully differentiated intrusions lie in the field of alkaline-ultrabasic rocks, and the points depicting their compositions are close to those of kimberlites and meimechites. Picrites of differentiated melanocratic intrusions correspond to alkaline picrites, and only the rocks from the ultrabasic horizon of differentiated leucocratic intrusions correspond to normal alkali-earth picrites.

Geological data pertaining to the sequence of formation of different types of intrusions and to their compositional characteristics suggest that the differentiation of the primary magmatic melts proceeds along two lines: the first one leads to the formation of differentiated leucocratic or melanocratic intrusions, and the second one to the development of fully differentiated or differentiated melanocratic intrusions. p.180
Differentiated melanocratic intrusive rocks are in both cases later formations. It would appear that one of the main factors determining the direction of segregation (or plutonic differentiation) is the total alkalinity of the primary melts predetermining not only the average composition of the intrusive rocks, but also the petrochemical type of the rocks composing individual horizons of the intrusions, including the ultrabasic horizon.

In discussing the problems related to the genesis of different sulphide-bearing massifs it is important to examine the behaviour of fugacious elements or of the fluidal phase of magmatic melts in the process of their segregation. Studies of the behaviour of fugacious components are among the most complex, but highly important petrological problems, and the ways to solve them remain so far obscure. Direct geological evidence often cannot be interpreted unambigiously. It had been believed for a long time with respect to the intrusions of the Noril'sk region that thick zones of contact metamorphism are characteristic only of fully differentiated massifs. It had been assumed that formation of metamorphic and metasomatic rocks is related to the separation of the fluidal phase from the melts. Studies of exocontacts from a number of differentiated intrusions of the Noril'sk region show that highly intensive contact alterations of the wall rock are not a prerogative of any given type of the intrusions examined, but may be observed around any of the massifs. Contact alterations and their intensity are determined to a significant degree by the lithology of the sediments enclosing the intrusion. On the other hand there is no doubt that the contact alterations related to differentiated intrusions are invariably much more intensive than those recorded around undifferentiated trap intrusions. This permits us to assert that the magmatic melts giving rise to differentiated intrusions generally have a higher content of the fluidal phase than common trap magmas.

Fig. 34



Petrochemical diagram showing the compositions of the rocks from sulphide-bearing differentiated intrusions of the Noril'sk region.

A-Alkali-earth rocks; B-Alkaline rocks with normative (standard) nepheline; C-Alkaline-feldspathoid rocks; I-IV---Intrusions of the Noril'sk region: I-Fully differentiated; II-Differentiated melanocratic; III-Differentiated leucocratic; IV-Undifferentiated; V-Kimberlites; VI-Meimechites; 1-3---Horizons of differentiated intrusions; 1-Picrites; 2-Olivine gabbro-dolerites; 3-Olivine-free gabbro-dolerites; 4-Average compositions of the intrusive rocks.

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Even though this is a highly significant conclusion, it does not by itself elucidate the behavioural patterns or the role of fugacious components in the formation of different types of differentiated massifs. In our opinion the most important evidence pertaining to this aspect of the problem has been obtained from studies on the structure, patterns of compositional variations and cryptic layering of the intrusions. p.181

A comparative analysis of these parameters from the three types of sulphide-bearing intrusions led us to conclude that the main differences in their composition and structure are due to the crystallization of melts supercooled to different degrees and varying in the content of fugacious components. The highest content of the fluidal phase and the highest degree of supercooling are characteristic of the magmatic melts of fully differentiated intrusions, and the lowest ones - of the melts of differentiated melanocratic intrusions. Silicate-oxide liquation that leads to the formation of a specific type of chromite ores [41] and is characteristic only of fully differentiated massifs, is an important proof of the high content of fluids in the melts.

It may thus be seen that not only petrogenic, but also fugacious components of the magmas separate in the process of differentiation (segregation) of primary melts, as a result of which there arise less basic melts that are rich in fugacious elements and have a higher alkalinity on the one hand, and "drier" melts with a higher basicity on the other. This pattern of differentiation convincingly explains the sequence of injection of intrusions, since the melts rich in the fluidal phase are more mobile and should run ahead of the "drier" melts in the process of migration of the magmatic column.

Analysis of the data pertaining to the distribution of ores in stratified intrusions shows the importance of magmatic differentiation processes in the separation of the silicate and sulphide components ultimately resulting in segregation of large mineral concentrations.

Prior to examining the conditions under which the sulphide components separate, we must try to elucidate the forms in which the sulphides may occur, and the state of sulphur in the silicate melts.

Thermodynamic data [123] show that under the conditions prevailing in the upper mantle, sulphides are stable phases, and that they therefore may be involved in the process of fusion during the formation of magmatic melts. Finds of sulphides in xenoliths from kimberlites evidence that sulphide compounds are stable at high temperatures and pressures.

Studies of basic magmatic melts in the regions of present-day volcanism [275] show that a sulphide liquid separated from the silicate melt by a clearly defined phase interface, is present in basic magmas at least during the period preceding the crystallization [232 and 262]. It is characteristic that sulphide agglomerations enclosed in a vitreous or crystalline silicate groundmass and measuring a few μm to several cm, have been encountered in basalts. It has been established that sulphide concentrations from the same magmatic formations may vary in chemical composition. Of considerable interest in this respect are the studies by B.J. Skinner and D.L. Peck [275], who detected variations in proportions of iron, nickel and copper in the sulphide globules co-existing with compositionally diverse silicate liquids. These data were the first evidence in support of the theory that the conditions of differentiation are the same for the silicate and sulphide components of magmatic melts.

Analysis of the distribution of the ore-forming components between the sulphides and silicates of the differentiated intrusions from the Noril'sk region also led us to conclude that during the formation of the intrusions, at least at the precrystallization stage, there exists a segregated sulphide liquid that is at equilibrium with the silicate melt [56 and 61]. The value of the coefficient of nickel distribution between the sulphides and olivine, the earliest solid phase, varies in a systematic manner from the horizon of ultrabasic rocks towards the horizon of basites and is a function of the temperature of the silicate melt coexisting with the sulphides. As the temperature rises, the concentration of nickel increases in the silicate liquid, and as it drops, the nickel content increases in the sulphide liquid. The discovery that the values of the distribution coefficients are the same for different types of intrusive rocks (for example, for the rocks of fully differentiated and differentiated melanocratic intrusions), is of great importance. It proves that, regardless of the total nickel concentration, which varies markedly in different types of intrusions, the composition of the sulphide liquid is entirely a function of the temperature and composition of the silicate melt and alters with changes in these parameters. p.18

Data on the solubility of sulphur in basic magmas are of great importance for assessing the state of the sulphide components in the melts. Studies of natural basaltic melts and experimental studies of some specific systems evidence that the solubility of sulphur in silicate melts is very low in spite of its being a function of their composition [221, 273 and 279]. Moreover, even the basaltoids yielding large masses of sulphur and the exhalation and hydrothermal products associated with it, have low solubility indices. This means that regardless of the concentration of sulphur in the magmatic system, sulphur can be fixed and can play an active role in the melts only under definite conditions. Proceeding from the characteristics of magmatic melts, assessment of the temperature conditions under which they exist [6 and 61], and results of experimental studies on the solubility of sulphur in the melts [120, 221, 273 and 279], it has been inferred that these conditions are as follows: 1) The presence of sulphur in the magma largely in the S^{2-} state on account of a high degree of ionicity* of high-temperature melts [70]; 2) The presence in the melts of significant concentrations of chalcophile elements, as well as of metals with chalcophile tendencies; and 3) A low oxygen potential and a sharply reducing character of the melt as a whole. Sulphur is fixed in the melt as a result of the formation of the chemical bond metal-sulphur, the statistical probability of which is proportionate to the concentration of chalcophile elements. The low oxidation potential of the melt predetermines a shift in the equilibrium of the reaction $MeS+O^{2-} \rightleftarrows MeO+S^{2-}$ towards the stability of the sulphide associates, as well as involvement in the processes of their formation not only of chalcophile elements, but also of a portion of petrogenic components, first of all of iron. These processes characterize the phenomena in the so-called second co-ordination sphere of the melt. In the first co-ordination sphere formed by the silicon-oxygen structural framework of the melt, the removal of a portion of cations on account of their forming chemical bonds with sulphur, leads to a rise in the degree of ionicity of the silicon-oxygen bonds and to a correspondingly sharp depolymerization of the melt. Intensification of the depolymerization effect is also due to the presence in the melt of fugacious components (particularly F, B and P) obstructing the formation of $Me - O - Si\equiv$bonds (where Me stands for petrogenic components) and thereby preventing the segregation of solid phases. The high concentration of sulphur, fugacious components and chalcophile metals in the magmatic melt is the main factor determining the direction of magmatic differentiation processes. The parallel action of the polarizing effect of sulphur on the silicate melt and of the effect of fugacious components contributing to the differentiation of petrogenic elements, lead to the separation from the primary melt of the relatively readily fusible sulphide-rich fraction of magma (fully differentiated intrusions) and to the formation of a melt enriched in relatively infusible components in the form of a magmatic residue (differentiated melanocratic intrusions). It is highly important that the prerequisite for this direction of the differentiation process is the presence in the melt of sulphide components in the form of molecular groups isolated statistically from the silicon- p.183 oxygen framework. In the course of the subsequent stages in the evolution of the melt these groups become progressively more segregated until they form concentrations with a clearly defined phase interface with the silicate liquid, and until large volumes of liquid sulphides separate and begin an independent existence. This is precisely the meaning of the primary immiscibility of the sulphide liquid in sulphide-silicate melts, which we set against the concept of the liquation origin of sulphide ores as it is formulated in the works [285] and [42].

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* Concentration of ions? Translator.

The processes of magmatic differentiation discussed above convincingly explain the sequence of formation of magmatic rocks observed at the deposits of the Noril'sk province, including the conditions under which the sulphide melts separate and are emplaced as a separate independent intrusive sub-phase.

CRYSTALLIZATION OF SULPHIDE MELTS AND CONDITIONS OF FORMATION OF COPPER-NICKEL ORES

The partition of sulphide components between the compositionally different magmatic melts, the segregation of substantial masses of the sulphide liquid and its emplacement in the form of an independent intrusive sub-phase after the injection of the sulphide-silicate melts are the factors accounting for the great diversity of forms observed among the mineral concentrations in the course of our studies on ores from deposits of the Noril'sk province. Explanation for most of the forms in which the mineral concentrations occur, can be found within the framework of the theories attributing the key role to the processes of magmatic differentiation of primary silicate melts containing an immiscible sulphide liquid.

Sulphide melts may crystallize in small or even very small volumes of the sulphide liquid dispersed in compositionally diverse melts, or in large volumes of that liquid invading intrusive or sedimentary-metamorphic rocks. In spite of the substantial differences in the environment, the development of the crystallization process is remarkably similar in the two cases. In practice there are no substantial differences between the formation of mineral associations resulting from the crystallization of one single drop of the sulphide liquid (e.g. amidst picrites of fully differentiated intrusions) and that of large volumes of the melt giving rise to deposits of massive sulphide ores.

Summing up the data on the mineral composition of the ores from the Noril'sk deposits described in chapter III, we may see that the parageneses of the ore-forming sulphides in all the types of the copper-nickel ores are associations of the same mineral species differing in chemical composition rather than associations of different ore minerals.

Juxtaposition of these data with the results obtained from the studies on the sulphide and sulphide-silicate systems modelling natural melts [192, 202 and 242] suggests that the main compositional characteristics of the sulphide liquid evolve at the stage of its coexistence with silicate melts, when an exchange of components between the two liquids is possible. After the separation of the sulphide liquid from the silicate melt or its conservation in microscopic quantities amidst the crystalline silicates, the composition of the sulphide liquid remains virtually unchanged both at the pre-crystallization stage and during the subsequent crystallization.

These general notions are a prerequisite for elucidating the patterns and conditions of formation of the paragenetic associations of sulphides from the copper-nickel ores of the Noril'sk province. Minerals of the group of pyrrhotite and those of the chalcopyrite group, pentlandite and cubanite, the phase relations between which are shown in the paragenetic diagram p.184
(fig. 35), form the basis of the paragenetic associations of sulphides. On the basis of the characteristic features recorded in

the paragenetic sequences of the copper-nickel ores there have been identified three main associations of ore-forming sulphides.

1. The sulphur-rich association represented by sulphides with the lowest values of ΣMe/S. The principal components of this association are monoclinic pyrrhotite, its intergrowths with hexagonal pyrrhotite, or hexagonal pyrrhotite alone. Minerals of the chalcopyrite group are represented by tetragonal chalcopyrite. The noteworthy feature of this paragenesis is the correlated increase of the concentration of iron (Fe,at.%) in minerals of the pyrrhotite group on the one hand and of the Fe/Ni ratio in pentlandite on the other, on the basis of which we can distinguish the following associations in the ores: $Po_{m16.6}+Cp+Pn_{0.8}$; $Po_{m46.6}+Po_{h47.0}+Cp+Pn_{0.8-0.9}$; and $Po_{h47.0-48.2}+Cp+Pn_{0.9}$.

2. The sulphur-poor association with the principal minerals characterized by the highest ΣMe/S ratios for each given group. This association comprises talnakhite, mooihoekite, cubic chalcopyrite, cubanite and pentlandite. Troilite may also be present. This association is somewhat different in impregnated and massive ores [$Tr+Mh(Tn,Cp_c)+Cub+Pn_{1.2}$ and $Mh(Tn,Cp_c)+Cub+Pn_{1.2-1.6}$, respectively].

3. The association of sulphides with intermediate values of ΣMe/S includes intergrowths of troilite and hexagonal pyrrhotite, lamellar or granular cubanite, ferroan or common tetragonal chalcopyrite, and pentlandite, The associations distinguished on the basis of the differences in their proportions of troilite and hexagonal pyrrhotite, iron content in pyrrhotite (Fe, at.%) and pentlandite (Fe/Ni), and of the presence or lack of ferroan chalcopyrite, are as follows: $Po_{h48.1-48.3}+Tr+Cp+Cub+Pn_{1.0-1.05}$; $Tr+Po_{h48.1-48.5}+Cp+Cub+Pn_{1.0-1.1}$; and $Tr+Cub+Pn_{1.1-1.3}$.

We now wish to examine the characteristics of these associations and their distribution in the main types of copper-nickel ores.

Fig. 35

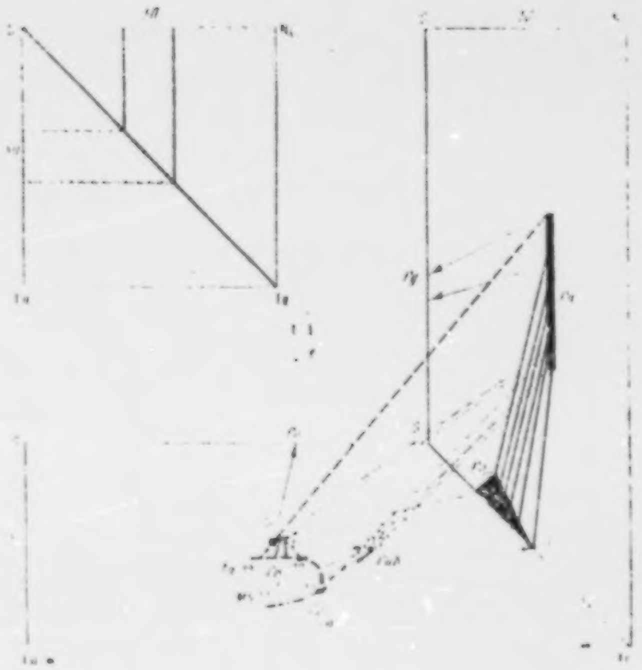

Diagram of paragenetic sequences of the principal ore-forming sulphides from copper-nickel ores.
Projection of a face of a Cu-Fe-Ni-S tetrahedron; continuous lines interconnect the minerals disposed in the plane of tetrahedron's faces, and dotted lines show the projection onto these faces.

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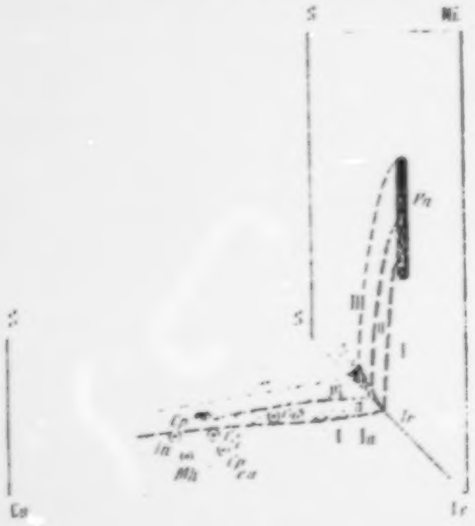
All the associations listed above are found in impregnated p.185
ores. The patterns of their distribution in differentiated intrusions are shown in the diagram (fig. 36). The main feature in the distribution of these paragenetic sequences of sulphides in different horizons of the intrusions is that sulphur-poor associations of sulphides occur only in the horizons of ultrabasic rocks, while intermediate or sulphur-rich associations may be localized in both ultrabasic and basic horizons. Moreover, the order of succession of these associations is invariably the same in each specific section of the intrusion. With transition from ultrabasic rocks to basites the $\sum$Me/S ratio in minerals of the pyrrhotite and chalcopyrite groups decreases in a systematic manner and the Fe/Ni ratio in pentlandite changes.

The distribution of mineral associations and variations in the composition of the coexisting minerals are described in the discussion of zoning and cryptic layering of sulphide ores from all the types of intrusions. This description suggests that the composition and parameters of state of the sulphide liquid at all the stages of consolidation of the magmatic melt are a function of the composition and parameters of the coexisting silicate liquid. Since the solidus of the sulphide melt is invariably lower than the solidus of the silicate melt, the sulphide melt may coexist with compositionally diverse silicate liquids, and the composition of these liquids varies depending on the patterns of crystallization of basic and ultrabasic magmas.

This means that the principal parameters affecting the composition of the sulphide melt, i.e. the fugacity of sulphur and the temperature, are specified as the parameters of state of the ambient silicate melt. The changes in the fugacity of sulphur vary from one stage of consolidation of the sulphide melt to another. The fugacity of sulphur is minimal in an environment with high temperatures and highly fugacious oxygen, but with a drop in the temperature of the sulphide melt coexisting with a lower-temperature silicate liquid, the fugacity of sulphur increases. Moreover, it should be stressed that the compositional heterogeneity of the sulphide liquid localized within small volumes of magmatic melt, testifies that there is no exchange of components between discrete portions of the sulphide material. The fugacity of sulphur within each micro-volume of the sulphide liquid is determined only by the coexisting silicate melt, and its crystallization leads to the conservation of each specific micro-volume of the sulphide melt with definite parameters of state. From this moment on the initial concentration of sulphur in the sulphide melt determines the sequence of its crystallization and subsequent changes in its f_{s_2}. At this stage the system may be regarded as closed with respect to the concentration of sulphur and other components. Proceeding from the temperatures obtained for the silicate associations, the equilibrium temperature at which p.186

conservation of the sulphide liquid occurs, varies within the range of 1400°C-1350°C for the early silicate associations to 1250°C-1115°C for the late silicates [61].

Fig. 36



Paragenetic associations of sulphides from impregnated ores of differentiated intrusions
I-III---Paragenetic sequences: I---from the central part of the picrite horizon of fully differentiated and differentiated leucocratic taxite gabbro-dolerite intrusions, Ia---from troctolites-picrites of differentiated melanocratic intrusions, II---from the upper and lower parts of picrites and troctolites-picrites in fully differentiated and differentiated melanocratic intrusions and from taxite gabbro-dolerites of differentiated leucocratic intrusions, and III---from taxite gabbro-dolerites of fully differentiated intrusions and marginal parts of all the horizons in each type of intrusions.

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The values of the fugacity of oxygen for basic melts within this temperature interval that can be derived from experimental data and from determinations of the fugacity of oxygen in natural systems, vary within the limits of $f_{o2}=10^{-6}-10^{-10}$ bars; moreover, the higher values characterize the state of the melt at the level of the horizon of picrite and troctolite gabbro-dolerites, and the lower f_{o2} values - its state at other vertical levels in the section of the magmatic column. The pattern of variations in the fugacity of oxygen will be different in each of the intrusive massifs examined, depending on the characteristics of the magma and conditions of its crystallization discussed earlier. The clear-cut differentiation of the melt during the formation of fully differentiated massifs accounts for the existence of fairly large oxygen fugacity gradients, while levelling of the parameters of state of the melt during the formation of differentiated melanocratic intrusions results in a relatively stable fugacity of oxygen. In fully differentiated massifs f_{o2} therefore decreases from the extreme horizon towards the upper and the lower contacts of the massif. The range of the f_{o2} variations for the sulphide-bearing horizons is 10^{-6} - 10^{-9} bars. In differentiated melanocratic intrusions most of the section of the magmatic column has a high and relatively stable fugacity of oxygen close to 10^{-6} bars. Since variations in the fugacity of oxygen and sulphur occur in opposite directions, it may be inferred that $f s_2$ will increase in the direction in which f_{o2} diminishes and that $f s_2$ should therefore rise from the extreme horizon towards the endocontacts of the intrusions. The minimum values of $f s_2$ for the high-temperature region of the sulphide melt that can be assessed for the conditions of the monovariant equilibrium metallic iron-troilite, come to 10^{-6} -10^{-9} bars.

It may thus be seen that the quantitative assessments of the temperatures, fugacity of oxygen and sulphur and their variations in the process of crystallization of stratified intrusions satisfactorily agree with the patterns of variations in the sulphur contents of sulphide parageneses from different intrusions and their individual horizons. Fig. 37 shows the patterns of variations in the sulphur contents of monosulphide solid solutions (Mss) from the section of the Talnakh intrusion, calculated on the basis of the quantitative mineral composition of real sulphide associations. The Mss with the lowest sulphur concentrations occur in the central part of the picrite horizon and fairly smoothly decrease in thickness towards the endocontact of the intrusion. As may be inferred from the data presented above, the composition of the Mss in differentiated melanocratic intrusions is practically constant almost throughout the sulphide-bearing part of the intrusion.

The content of ore-forming components in the sulphide liquid is directly a function of the temperature and fugacity of sulphur. However, $f\,s_2$ is probably the main factor in the melt affecting its crystallization, since upon the completion of the crystallization of silicates the sulphide melt is a closed system in relation to sulphur. The general crystallization patterns of sulphide systems in natural and experimental materials have been inadequately studied in the literature. We are, however, able /to analyze/for the first time/such a large compositional range of sulphide liquids in genetically integral systems on the basis of natural paragenetic sequences.

Distinctive compositional characteristics of the sulphide liquid at different parameters of state are reflected in the compositional diversity of the crystallizing Mss. First of all, the differentiation of the sulphide liquid into two melts results in the occurrence of two types of solid solutions [chalcopyrite (Iss) and nickel-pyrrhotite (Mss)] that are at equilibrium. Analysis of their paragenetic sequences clearly shows the agreement between the two phases with respect to their sulphur contents and proportions of ore-forming components. Low-sulphur Mss invariably p.187 coexist with low-sulphur Iss. The most important characteristic of solid solutions is that variations in their composition are a function of activity ratios of their ore-forming components at the given $f\,s_2$. For example, the Mss crystallizing at low $f\,s_2$, are virtually free of nickel, have low sulphur contents and a composition with Me/S=1. In the low-temperature region the product resulting from solid-phase alterations of an Mss with this kind of composition is a troilite enclosing no lamellas of pentlandite and containing 0.01% or less of Ni in the solid solution. Under these conditions the total nickel concentrates in the residual liquid, crystallization of which produces an iron-rich pentlandite. The composition of pentlandite in this association does not vary as a function of the total nickel concentration, but is controlled by the activity ratio of Fe and Ni. This has been convincingly demonstrated by the juxtaposition of associations with identical sulphur contents from fully differentiated (nickel-rich) and differentiated melanocratic (nickel-poor) intrusions. The main difference between these associations is the quantity of pentlandite that is greater in the nickel-rich intrusion, rather than the composition of the mineral as such. As $f s_2$ increases, the content of sulphur in Mss rises. This is reflected, among others, in the varying proportions of troilite in its intergrowths with hexagonal pyrrhotite, and in the subsequent appearance of paragenetic sequences with hexagonal pyrrhotite. As $f s_2$ increases, the solubility of Ni in Mss rises and the Fe/Ni ratio in pentlandite decreases. The latter fully agrees with the data in [260]. It has been established experimentally [282] that the sulphur content in pyrrhotite may vary as a function of the temperature at a constant $f s_2$. Variations in the sulphur contents of pyrrhotite from the paragenetic sequences examined are conjugated, however, with variations of its nickel concentrations in the solid solution, as well as with variations in the contents of iron in the coexisting pentlandite. This evidences that the composition of Mss and pyrrhotite is mainly a function of variations in the fugacity of sulphur.

Phase relations of the sulphides crystallizing from a p.188
copper-rich liquid, correspond to the associations that have been experimentally studied in the Cr-Fe-S system. The field of a solid solution [237,290 and 15], the unmixing of which results in the formation of complex sulphide associations, has been identified in the high-temperature region of that system. The composition of these associations depends to a significant degree on the ratios of the concentrations (activities) of cations and Me/S magnitude in the melt. The phase relations in the sulphide associations of differentiated intrusions can be used to demonstrate that the pattern of variations in the composition of the copper-rich liquid is generally similar to that in the composition of the pyrrhotite liquid. The copper-rich melt coexisting with high-temperature silicates, is characterized by the ratio $\sum \mathrm{Me/S} > 1$.

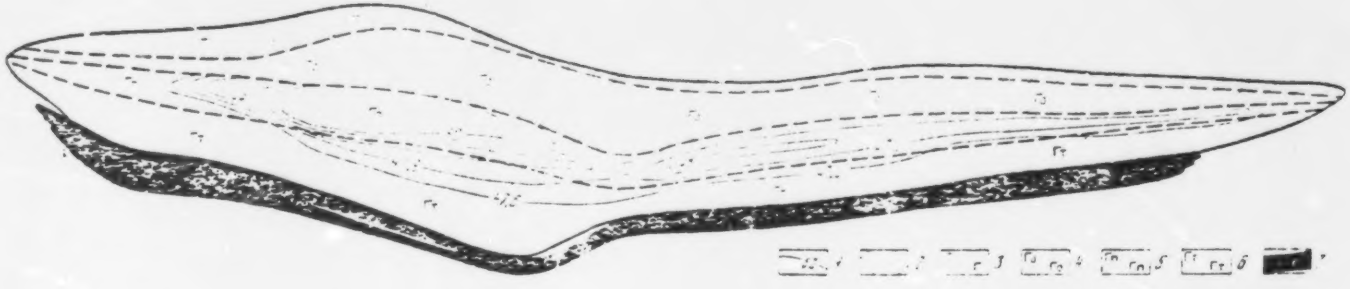


Fig. 37

Variations in the composition of the monosulphide solid solution in the section of the fully differentiated intrusion at Talnakh

1-Isolines of the composition of Mss (Me in at.%); 2-Sulphide-free horizons of the intrusions; 3-6---The main petrographic horizons of the intrusions; 3-Gabbro; 4-Olivine-containing or olivine gabbro-dolerites; 5-Picrites; 6-Taxite gabbro-dolerites; 7-Massive ores.

In the environment characteristic of that type of melt the fugacity of sulphur is probably low at the temperature of the sulphide-silicate equilibrium of about 1350°C. The product crystallizing from that type of melt is a sulphur-poor Iss, the exsolution of which in the subsolidus region results in the formation of the assemblage of minerals of the chalcopyrite group ($Tn+Mh+Cp_c$) with $\sum Me/S > 1$. The total variations in the $\sum Me/S$ ratio in the melt are probably fairly great, since the proportions of the above phases vary widely in the ores.

The ratio of activities of the ore-forming cations in the melt is an important factor in the formation of the mineral composition of sulphide associations. In an environment with a low fugacity of sulphur the activity of the cations with the greatest affinity to sulphur is higher. Crystallization of such melts results in the formation of Iss that are relatively rich in iron and the exsolution of which leads to the formation of iron-rich phases. Troilite-mooihoekite (sometimes talnakhite or cubic chalcopyrite), the paragenesis corresponding to the conditions with the minimal fugacity of sulphur, is one of the most characteristic paragenetic sequences of differentiated intrusion. Progressive increase of $f s_2$ provides for the formation of troilite-ferroan chalcopyrite associations and of associations of troilite with cubanite and tetragonal chalcopyrite. However, as may be seen from the paragenetic diagram in fig. 35, the troilite-tetragonal chalcopyrite association cannot be stable, since in the melts with a $f s_2$ corresponding to the stability of troilite, $a_{Fe} > a_{Cu}$ and Iss will have a higher content of iron than that needed in the melt for tetragonal chalcopyrite to form. The composition of such an Iss is independent of the total copper concentration in the melt. This appears to be the main reason for the extensive development of cubanite in the sulphide associations examined; cubanite occurs here not only in the form of exsolution lamellas in chalcopyrite, but also forms large discrete concentrations. Crystallization of a copper-rich sulphide liquid coexisting with lower-temperature associations of silicates and having higher $f s_2$ values, leads to the formation only of tetragonal chalcopyrite that is stable with pyrrhotite containing various quantities of sulphur, and with nickel-rich pentlandite.

We have thus demonstrated that the systematic evolution of the composition and of the fugacity of sulphur in the immiscible sulphide liquid in a sulphide-silicate basaltic magma is the main factor controlling the distribution, zoning and cryptic layering of sulphide associations in stratified intrusions.

Massive ores. Comparison of the paragenetic associations of massive ores with the parageneses of impregnated ores that have been examined earlier shows that 1) the paragenetic sequences of the principal ore-forming minerals are identical in the two types of ores (excepting the mooihoekite-troilite association that is lacking in massive ores); 2) the principal associations composing spatially segregated mineral varieties of massive ores, include bornite-godlevskite-millerite and chalcopyrite-heazlewoodite assemblages that are absent from impregnated ores; and 3) the mineral association of noble, rare and disseminated elements completing the process of ore formation, has a relatively wider distribution and a considerably more p.189 varied mineral composition in massive ores.

As was demonstrated earlier, the sulphide liquid, from which massive ore bodies crystallize, is a product of plutonic differentiation of the sulphide-silicate melt. The fact that the composition and paragenetic associations of principal minerals are identical in massive and impregnated ores shows that the two sulphide liquids (the liquid persisting in the silicate melt and that separating in the form of an independent sulphide melt) are at equilibrium with the same silicate melt. The state of equilibrium predetermines identical concentrations of sulphur and ore-forming components in the sulphide liquids, as well as similar patterns and sequences of crystallization of the melts. These are precisely the reasons for the similarity of the processes resulting in the formation of mineral associations, be it on the scale of an isolated inset, or in a volume of melt forming a large ore body.

The factors controlling the distribution of mineral associations in zones are, however, different for each type of ores. In impregnated ores the main factor is the coexistence of different volumes of the sulphide liquid with silicate melts varying in composition and parameters of state.

The separation of the sulphide liquid from the silicate melt and its independent emplacement mark in fact its transition to a closed system, at least with respect to the principal ore-forming components. We can only mention relatively unimportant contact oxidation reactions of the sulphide liquid leading to the crystallization of considerable amounts of magnetite in the narrow contact-line zone.

The main factors in the crystallization of such liquids and in the formation of mineral zoning in the ore bodies are the rate of cooling of the melt, the sulphur regime in the melt, and the behaviour of the components varying in fusibility.

Having analyzed the distribution of the mineral associations, we have formulated a theory according to which the zoning in the bodies of massive sulphide ores [56] is of two types tentatively designated as simple and complex zoning.

By simple zoning we refer to the changes in the proportions of pyrrhotite and chalcopyrite as the pyrrhotite ores gradually alter to the chalcopyrite variety. Complex zoning refers to the succession of numerous mineral varieties of ores, among which the principal ones are represented by the pyrrhotite → cubanite → mooihoekite (talnakhite) series.

The conditions of crystallization of the pyrrhotite and chalcopyrite ores forming series of mineral varieties of massive ores with simple zoning, were investigated experimentally in the course of the research on the Cu-Fe-Ni-S system [197]. The results obtained from the studies on that system show that during the cooling of sulphide melts at the stage of early crystallization there forms an iron-nickel monosulphide solid solution which may also contain a limited amount of dissolved copper. The residual melt becomes enriched in copper and crystallizes at 850°C with a break of about 200°C relative to the temperature at which the crystallization of the monosulphide solid solution begins. The model of the eutectic crystallization of two-component systems with different fusibility and limited miscibility levels of the primary components may serve as a simplified theoretical model for this type of zoning.

This fractional crystallization model of the sulphide melt explains many relations of pyrrhotite and chalcopyrite aggregates in massive ores. The later crystallization of the copper-rich melt in the pyrrhotite ores finds its expression in the knitted arrangement of chalcopyrite around the large pyrrhotite grains containing pentlandite in the form of exsolution products. Crystallization differentiation of the sulphide melt also leads to the segregation of masses of the residual melt enriched in copper, noble and rare metals at the contacts and in the pinch-out p.190 zones of the deposits. The residual melt appears to be an eutectic liquid, from which chalcopyrite and agglomerations of the so-called second-generation pyrrhotite crystallize.

The cryptic layering associated with this type of zoning, testifies to the formation of the mineral associations under conditions of a steadily growing fugacity of sulphur. This is precisely the factor explaining the steady decline of the Me/S ratios in pyrrhotite and Fe/Ni in pentlandite from the central part of the deposits towards their contacts.

The mechanism of crystallization differentiation of the sulphide melt is not, however, an adequate basis for explaining the distinctive aspects of the development of massive ore deposits with complex zoning that are typical of the Talnakh ore field. Segregation in space of large volumes of copper-rich ores represented by the mooihoekite and talnakhite varieties, and extensive development of cubanite ores inbetween the pyrrhotite and mooihoekite (talnakhite) varieties, are the features characteristic of this type of deposits. It is important to note that in the course of the experimental studies there has been obtained no evidence showing that cubanite can crystallize directly from the sulphide melt.

It appears probable that deposits with complex zoning evolve in the process of the high-temperature differentiation of the sulphide melt into an iron-rich melt with a high sulphur content on the one hand, and a copper-rich low-sulphur melt on the other, which subsequently crystallize in the form of pyrrhotite and mooihoekite (talnakhite) ores. Cubanite ores arise, however, as a result of exchange reactions between the fractions segregating from the melts and, partly, between the products of their crystallization.

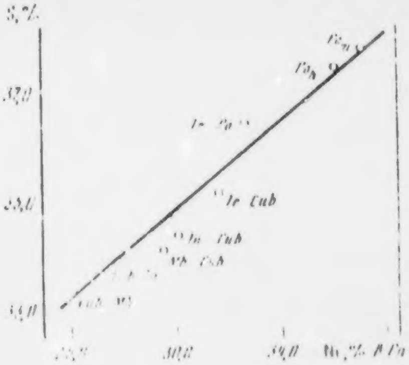
The difference in the sulphur contents in the melts is evident not only from the presence of minerals differing in the $\sum$Me/S ratio, but also from the presence of those with a constant $\sum$Me/S, but with varying proportions of cations. It has been established, for example, that the composition of pentlandite is clearly a function of the total sulphur in the melt (fig. 38).

Specific aspects of the distribution of ore-forming and rare elements in massive ores with zoning of the simple and complex type, respectively, also testify that they crystallize under different conditions [56].

One of the factors responsible for the occurrence of different types of zoning in massive ores, is the difference in the temperature conditions during the cooling of the melts. Simple zoning arises at high temperature gradients with a relatively rapid cooling of the melts. Complex zoning that is characteristic only of large massive ore deposits, appears to evolve under conditions of a slow cooling providing for the maximum segregation of the copper-rich melt. The specific behaviour of sulphur and the differences in the mineral associations and in the composition of the ore-forming minerals controlled by it, are also related to the differences in the temperature conditions during the cooling of the melts.

Veinlet-impregnated and brecciated exocontact ores differ from all the other types of ores in that their constituent sulphides belong to the paragenetic sequences with the highest sulphur concentrations. Monoclinic pyrrhotite associating with tetragonal chalcopyrite and pentlandite, is the only pyrrhotite group mineral found in these ores. The content of nickel in pyrrhotite and pentlandite of these ores is higher than its contents in these minerals from massive or impregnated pyrrhotite ores.

Fig. 38



The content of nickel in pentlandite of massive ores as a function of the total sulphur content.

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The following features testify that monoclinic pyrrhotite forms as a result of subsolidus alterations of a high-sulphur Mss crystallizing from sulphur-rich melts, rather than by way p.191
of replacing hexagonal pyrrhotite: 1) There are no relicts of hexagonal pyrrhotite in exocontact ores; if monoclinic pyrrhotite had formed under the effect of mineralizers from hexagonal pyrrhotite, relicts of the latter should have persisted here and there; the phenomena of hydrothermal metamorphism observed in these ores lead, however, to the replacement of monoclinic pyrrhotite by aggregates of pyrite and magnetite; 2) Intergrowths of monoclinic pyrrhotite with unaltered silicates (forsterite, pyroxene) and the phenomena mentioned earlier, i.e. the recrystallization of forsterite and pyroxenes (see Plate IV,a) around the pyrrhotite veinlets with an increase in the size of their particles; and 3) The presence of veins of massive sulphides amidst the brecciated exocontact ores with loci of veinlet-impregnated ores, and the direct transition of massive to brecciated ores.

We must therefore conclude that the principal primary associations of exocontact ores evolved during the crystallization of the sulphide melt, although the mechanism of its penetration into the sedimentary-metamorphic rocks has not been adequately clarified as yet. The high capability of the melt to impregnate the wall rock may be due to its increased mobility (i.e. decreased viscosity).

The process resulting in the development of zoning in this type of ores is in fact a continuation of the process of crystallization of massive ores. This is evident first of all from the similarity in the composition of massive and veinlet-impregnated ores. For example, in the parts of the deposits composed of massive pyrrhotite ores, the veinlet-impregnated ores predominating in their exocontact, are also of the pyrrhotite variety. In the locales composed of mooihoekite or talnakhite ores, the mineral concentrations developing in the wall rock are represented by mooihoekite, talnakhite or cubanite impregnations. These mineral associations are, however, generally rare and the bulk of the sulphide minerals composing the veinlet-impregnated ores, is represented by high-sulphur associations distributed in the ore bodies in accordance with the mechanism governing the formation of simple zoning.

MINERAL ASSOCIATIONS FROM THE FINAL STAGES OF ORE FORMATION

The group of minerals evolving at the final stages of ore formation is highly varied. Proceeding from the characteristic aspects of their occurrence in the ores, we distinguish two associations differing in their relations with the principal ore-forming sulphides.

The formation of one of these assemblages concludes the process of development of massive and veinlet-impregnated (but not impregnated!) ores. This association is represented by bornite, millerite, godlevskite, as well as by chalcocite and heazlewoodite forming fairly large concentrations in the periphery of the ore bodies. A characteristic feature of nickel and copper sulphides is the marked predominance of metal over sulphur in their composition, as a result of which their Me/S ratio is commonly 1.5 to 2. The feature common for the associations of these sulphides is their formation in an environment with a relatively low activity of sulphur. The paragenesis with the lowest sulphur concentration (intergrowths of chalcocite with heazlewoodite) develops in the form of veins around the locales of talnakhite ores in massive ore deposits. The same paragenetic sequence and the association of bornite and godlevskite have also been observed amidst the veinlet-impregnated and sideronitic ores occurring at the contacts with talnakhite and mooihoekite ores in gabbro-dolerites.

The second association amalgamates a large variety of minerals of noble, rare and disseminated elements. These minerals crystallize later than the principal ore-forming sulphides and become deposited in the form of veinlet-like aggregates or metacrysts in the periphery, as well as in the central part of the ore bodies. They occur in all the types of ores, but have been encountered most frequently in the copper-rich varieties of massive or exocontact ores. p.192

The most typical representatives of the ore minerals forming in the process of residual mineralization are djerfisherite, shadlunite, thalcusite, argentopentlandite, cuproan pentlandite, sphalerite, galena and minerals of platinum metals. Being members of the same paragenetic association, these minerals occur in the ores together, as well as separately. All these minerals contain elements that are either lacking or are found in negligibly small concentrations in the principal ore-forming sulphides. These elements accumulate only in the residual fluids.

Some notions regarding the composition of the residual fluid can be inferred from the presence in that association of djerfisherite, a chlorine-containing sulphide of potassium, copper and iron evolving in massive talnakhite ores by replacing pentlandite or occurring in the form of metacrysts in talnakhite. Potassium (0.4%) was recently identified in thalcusite (a sulphide of copper, iron and thallium) in addition to djerfisherite. The composition of shadlunite (a sulphide of copper, iron, lead, cadmium and manganese) and those of the galena, sphalerite and alabandite coexisting with it, testify that these minerals crystallize in an environment where the components are at equilibrium with regard to their distribution. It is characteristic that the composition of shadlunite corresponds to that of the sphalerite coexisting with it. Cadmium-rich sphalerite occurs in intergrowths with cadmium-rich shadlunite, while alabandite, as well as sphalerite with increased concentrations of manganese occur in intergrowths with Mn-shadlunite.

Comparison of the compositions of the minerals from this group shows that they contain two types of elements: 1)Copper and iron inherited from the principal ore-forming sulphides, from which these minerals evolved by way of substitution; and 2)Potassium, chlorine, lead, cadmium, manganese, silver and thallium accumulated in residual fluids.

Typical representatives of the paragenetic associations evolving at the stage of residual crystallization of sulphide melts, are minerals of platinum metals. They are represented by compounds of the following binary and trinary systems: Pt-Fe, Pt-Sn, Pd-Sn, Pd-Sn-Cu, Pd-Sn-As, Pd-Sn-Sb, Pd-Pb, Pd-Bi, Pd-Pb-Bi, Pd-As, Pd-Ni-As, Pt-Te,Bi, Pd-Te-Bi, Pt-S, Pd-Ni-S and Pt-Pd-Ni-S. It should be stressed that palladium-lead and palladium-tin-copper compounds are characteristic only of the Noril'sk ores and have not been encountered at any other occurrences of copper-nickel ores.

The formation of platinum minerals later than of the principal sulphides evolving during the crystallization of the sulphide melt, is at variance with the crystallization temperatures of a number of platinum and palladium compounds in dry systems. Pt, Pd, Pt_3Sn, PtSn, Pd_3Sn, Pd_2Sn, Pd_3Sn_2, Pd_3Pv and Pd_3Sb, mineral analogues of which have been identified in the ores, crystallize in the Pt-Sn, Pd-Sn, Pd-Pb and Pd-Sb systems within the 1773-1220°C temperature interval that is much higher than the crystallization temperature of the monosulphide solid solution (1100°C), the highest-temperature compound of copper-nickel ores.

The characteristic aspects of the occurrence of platinum metal minerals in the ores [i.e. a)the morphology of their grains that are often represented by metacrysts with inclusions of the surrounding minerals, b)the veinlets of platinum minerals cutting across pyrrhotite, chalcopyrite and pentlandite, c)the concentration of the grains of platinum minerals along the selvages of some veins and deposits, their upper selvage in particular, where these minerals associate with magnetite and, in some places, with apatite, and d)the close association of platinum minerals with galena, sphalerite, djerfisherite and shadlunite] testify that platinum minerals form later than the principal sulphides of copper-nickel ores [20]. Of interest are the relations of platinum minerals with djerfisherite. Platinum minerals (polarite, majakite, etc) form agglomerations of grains with djerfisherite and overgrow it here and there in the form of slender borders.

Platinum minerals therefore probably crystallized from the fluids which segregated from the sulphide melt and contained p.193 fugacious components in addition to the platinum group and other metals, rather than directly from the melt. The participation of fugacious components in formation of the ores is evident from the presence in these ores of minerals containing OH, Cl and F, as well as of the potassium- and chlorine-containing djerfisherite associating with platinum minerals.

Platinum-bearing fluids concentrated in the copper-rich melt that was the last one to crystallize. In addition to platinum and palladium, these fluids were enriched in elements, such as tin, lead, arsenic, antimony, bismuth etc. that are present in negligibly small quantities in the basic magmas. The fluids were distributed in the sulphide melt in the form of dispersed drops from which platinum minerals crystallized after the crystallization of chalcopyrite and other sulphides.

The distinctive feature of platinum mineralization in the Noril'sk ores that is important for clarifying the conditions under which these ores formed, is that the forms in which platinum minerals occur, are determined by the type and composition of the copper-nickel ores. Particularly striking differences in the composition of platinum minerals have been established in massive pyrite and chalcopyrite (talnakhite and mooihoekite) ores and by comparing impregnated, massive and exocontact ores.

Massive pyrrhotite ores contain small quantities of the minerals of platinum metals represented by minutest grains of sperrylite, ferroplatinum and rustenburgite (Pt_3Sn). It has been noted that platinum minerals are confined largely to chalcopyrite disposed inbetween the grains of pyrrhotite. Various intermetallic compounds of palladium predominate in massive talnakhite and mooihoekite ores.

The ores impregnated in intrusive gabbro-dolerites are similar to massive pyrrhotite ores because of the predominance of platinum minerals in them, but they differ from the latter on account of their fairly high content of cooperite, a sulphide of platinum lacking in massive ores.

The characteristic features of the composition of the minerals of platinum metals from exocontact ores are the abundance of cooperite (in both pyrrhotite and chalcopyrite ore varieties) and the presence of braggite, vysotskite, platinum and palladium tellurides and bismutotellurides in chalcopyrite ores.

These data evidence that in spite of a certain autonomy of the process of formation of platinum minerals, it is invariably co-subordinate to the process of development of the associations composing the principal sulphides. This co-subordination is expressed in the formation of intermetallides and other compounds of platinum metals rather than of sulphides in the ores with low-sulphur associations of the principal minerals. Platinum and palladium sulphides crystallize only during the process of formation of high-sulphur paragenetic sequences of the principal sulphides.

There have now also been elucidated patterns of a more general nature in the formation of platinum minerals on the basis of analyses of the distribution of platinoids between the minerals of copper-nickel ores [33] and experimental studies of some sulphide systems containing platinum metals [60].

These patterns are determined by the following characteristic aspects of the behaviour of metals during the crystallization of sulphide melts [60]: 1)A sharp partition of platinoids between the early solid-phase products and the residual melt; and 2)Formation of solid solutions of platinoids in the ore-forming sulphides. The partition of platinoids between the residual melt and the early solid-phase products occurs on account of the accumulation of platinum and of a significant portion of palladium in the former, while the rare platinoids and, partly, palladium co-precipitate in monosulphide solid solutions. It has been established experimentally that the amounts of rhodium, ruthenium, iridium and osmium occurring in pyrrhotite and pentlandite in the form of solid solutions, are several orders above the real concentrations of these metals in the ores [60]. Moreover, the solubility of these metals is a function of the fugacity of sulphur in the system, so that the $\sum$ Me/S ratio in pyrrhotite and Fe/Ni in pentlandite are invariably determined by the contents in these minerals of platinoids. p.194
The high solubility in the Mss of rhodium, ruthenium, iridium and osmium at a high f_s at the early stage of crystallization of the sulphide melt is precisely the factor accounting for the absence of the minerals of these metals from the ores. This is also the reason for the negligibly low contents of palladium minerals in pyrrhotite ores, since palladium occurs almost entirely in the form of an isomorphous admixture in pentlandite [37 and 60]. Analysis of the distribution of palladium in pentlandite [37] shows that the solubility of palladium declines sharply with a decrease of f_{s2}, which is one of the main prerequisites for the formation of a greater number of palladium minerals in talnakhite and mooihoekite ores than in chalcopyrite ores.

HYDROTHERMAL METAMORPHISM OF THE ORES

In contrast to what has been observed at most copper-nickel deposits, e.g. those at Pechenga, metamorphic alterations play a secondary role in the ores of Noril'sk. Metamorphic mineral associations have been encountered most often in veinlet-impregnated ores from the exocontact aureole of gabbro-dolerite intrusions, and are less widely distributed in other types of ores.

The principal minerals of these late paragenetic assemblages are pyrite, nickeloan pyrite, magnetite, minerals of the valleriite-tochilinite group, millerite and polydymite. Relicts of minerals from the early paragenetic sequences may be found in intergrowths with these minerals.

In massive ores the locales composed of the late associations are commonly confined to the postmineral disturbances displacing the deposits of massive ores. Aggregates of pyrite or its intergrowths with magnetite appear amidst pyrrhotite masses composed entirely of monoclinic pyrrhotite. In the absence of pyrite there have been observed intergrowths of monoclinic pyrrhotite with hexagonal pyrrhotite which it replaces. Monoclinic pyrrhotite appears to form in these locales as a result of the removal of iron from hexagonal pyrrhotite by late hydrothermal solutions [25].

A wide-spread phenomenon in the exocontact ores other than the replacement of pyrrhotite by pyrite and magnetite is the break-up of pentlandite and the occurrence of aggregates of the nickeloan pyrite+millerite or millerite+polydymite association in its place. Vysotskite (Pd, Ni)S has been observed here and there in intergrowths with these newly formed minerals. Its appearance in the pseudomorphs in pentlandite is related to the mobilization of isomorphous palladium from the structure of pentlandite [22].

A characteristic feature of the minerals from the late paragenetic sequences is that their composition depends on the composition of the minerals replaced. In addition to the examples discussed earlier, it can be readily observed in minerals of the valleriite-tochilinite group. In massive ores, where the predominant minerals are chalcopyrite, cubanite or talnakhite, the mineral arising as a result of their replacement is valleriite $CuFeS_2 \cdot 1.37Fe(OH)_2$, whereas in impregnated exocontact chalcopyrite ores from magnesian rocks the component predominating in the valleriite replacing chalcopyrite in the hydroxide layers is brucite $CuFeS_2$. 1.51 (Mg, Fe)$(OH)_2$. When pyrrhotite becomes replaced in exocontact pyrrhotite ores, there evolve intergrowths of a copper-poor valleriite with a tochilinite, the sulphide component of which is represented by a sulphide of iron. Magnetite and pyrite have been encountered most often in the paragenetic association with minerals of the valleriite-tochilinite group.

The paragenetic sequence of relatively rare minerals represented by nickeline, breithauptite, maucherite, safflorite, loellingite, rammelsbergite, gersdorfite, ullmannite and native arsenic, is a metamorphic association.

This paragenesis arises on account of the galena- and sphalerite-containing calcite veins cutting across the pyrrhotite p.195 ores. The sources of nickel, cobalt and iron for this paragenetic association were pyrrhotite and pentlandite, from which these metals were extracted by the metamorphosing solutions that supplied arsenic and antimony.

The mineral associations examined above are the only manifestations of metallic mineralization at the Noril'sk deposits associated with a certain type of alterations of the country rock. The composition of the newly formed (secondary) nonmetalliferous minerals depends entirely on the composition of the wall rock. In calcareous rocks these secondary products are represented by wollastonite-vesuvianite, epidote-vesuvian, as well as hydrogarnet-serpentine and apophyllite-xonotlite metasomatic rocks. Serpentine and brucite metasomatites are widely distributed in magnesian rocks.

The inert behaviour of the principal metals (Ni,Cu,Fe and Co) and petrogenic elements (Mg,Al and Si) during the formation of the minerals is thus the main characteristic of the latest hydrothermal paragenetic associations, and the type of the paragenesis is determined by the activity ratios of H_2O, CO_2, S, As, Sb and F. This is precisely the circumstance that permits us to regard the paragenetic sequences described as associations of hydrothermal metamorphism of ores. The process of metamorphism appears to be of a relatively low-temperature kind. This is supported by the homogenization temperatures of the gas-liquid inclusions in calcite and sphalerite (105-230°C).

CONCLUSIONS

The main features of the formation of sulphide ores in the Noril'sk province, one of the most interesting copper-nickel provinces in the world, are examined in this work. That province owes its unique character primarily to the fact that it is the only area in the enormous trap region of the Siberian platform, in which there occur specific magmatic formations associated with the conveyance of large masses of mineral material to the upper horizons of the earth crust. These magmatic formations are represented by extrusive ultrabasic lavas conjugated with basic volcanic rocks, and by differentiated intrusions that contain ultrabasic horizons arising as a result of differentiation of basic magmatic melts.

The theory that extrusive and intrusive rocks belong to the same volcanic-plutonic association, is substantiated in this work. The two types of rocks have many petrological features in common and high concentrations of metallogenic elements. Sulphide mineralization is associated, however, only with differentiated intrusive rocks.

In the Noril'sk province there have been distinguished three types of differentiated intrusive rocks differing in contents of sulphides and in stratification patterns. The characteristic features of these intrusive rocks are the fact that they always occur together, and a definite sequence of injection.

The key factors in the formation of different types of intrusive rocks are the processes of plutonic magmatic differentiation which resulted in the separation of petrogenic components and sulphide material. These notions provide a more convincing explanation for the age and space relations of the intrusive rocks than the hypotheses postulating their formation from magmatic melts forming during the sequential fusion of the upper mantle's substratum.

The least developed aspects in the concept of the magmatic genesis of copper-nickel ores are those directly related to the clarification of the conditions under which the ores formed. A highly important concept for understanding the patterns of formation of sulphide ores, including the causes and conditions of formation of large mineral concentrations, is the concept of the immiscible sulphide liquid as the principal structural-chemical state of metallogenic components in the basic magma. The immiscible sulphide liquid participates in the whole complex of the phenomena related to the inception and existence of the basic melt.

The cryptic layering of sulphide ores, identified for the first time as a fundamental property of magmatic ores, proves that the composition of the sulphide liquid alters as a result of changes in the parameters of state of the co-existing silicate melt. It has been demonstrated that an equilibrium exchange of components controlled by the temperature and by the regime of the fugacious components of the magma, occurred at all the stages between the immiscible sulphide liquid and silicate liquid. It is suggested that the sulphide liquid is one of the main factors responsible for the formation of layering in the intrusions.

The fact that the processes of rock and ore formation are interrelated is the reason for the diversity of the conditions under which magmatic sulphides become deposited. This is reflected first of all in the extraordinarily varied mineral composition of the ores. The distinctive aspects of mineralogy established in the copper-nickel ores, are as follows. At the early stages p.197
of ore formation the paragenetic sequences of magmatic sulphides comprise a limited number of mineral species, but changes in the conditions of minerogenesis lead to extensive variations in the chemical composition of individual mineral species. Compositionally diverse paragenetic sequences, including the associations of platinum minerals and numerous minerals of rare or disseminated elements, form at the final stages of the deposition of ore from the residual melts.

The fact that the processes of formation of differentiated intrusive rocks are interrelated with those of copper-nickel ores accounts for the development of the mineral-petrological zoning in deposits and ore field.

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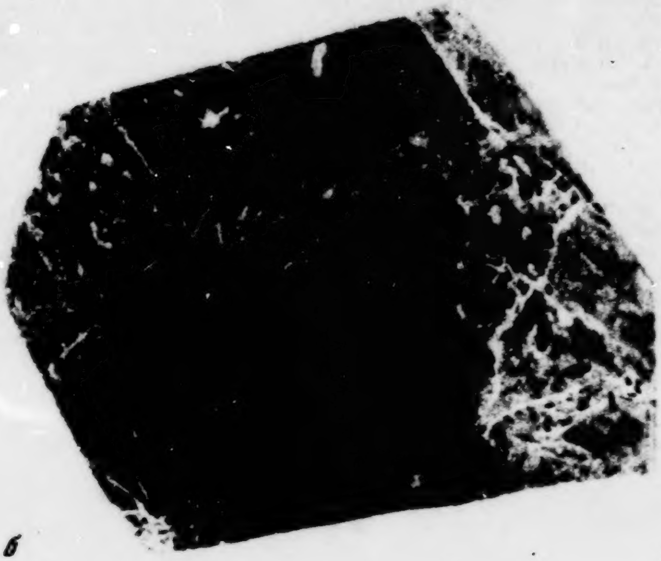

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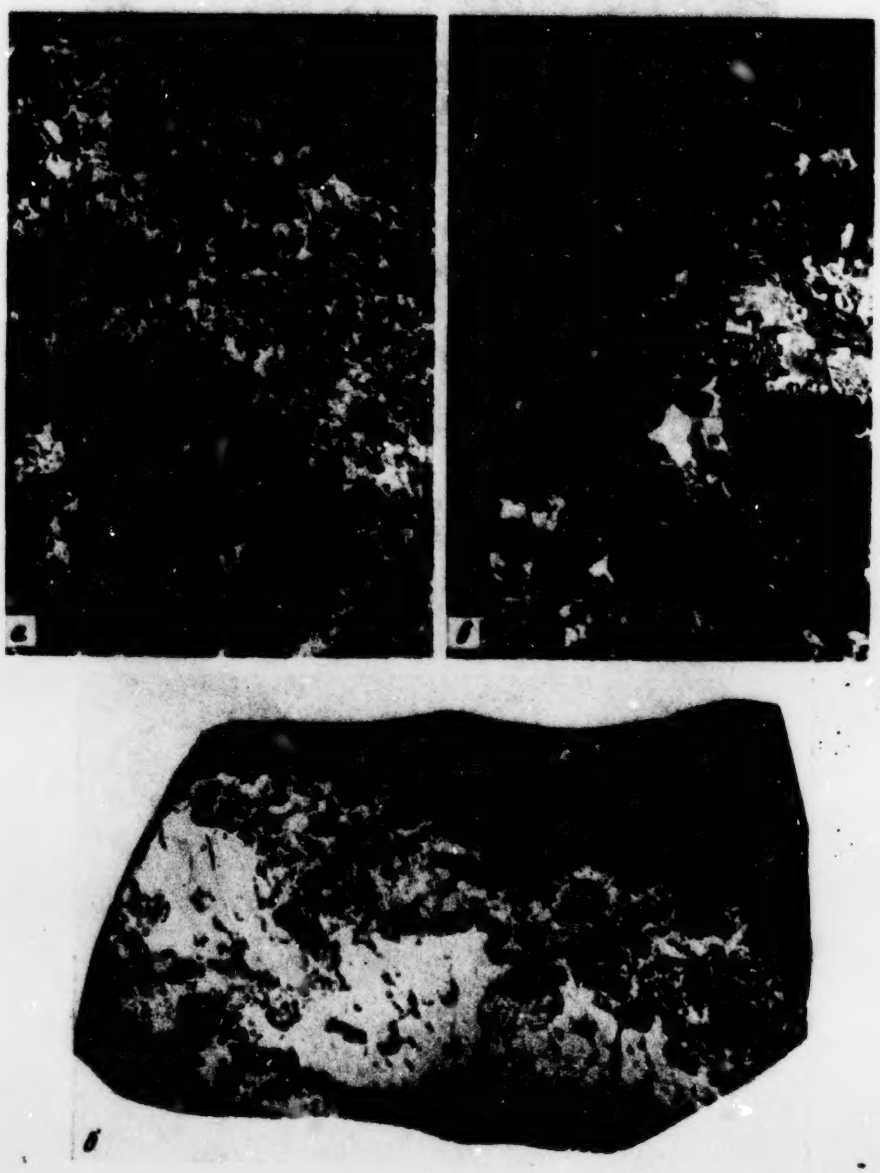
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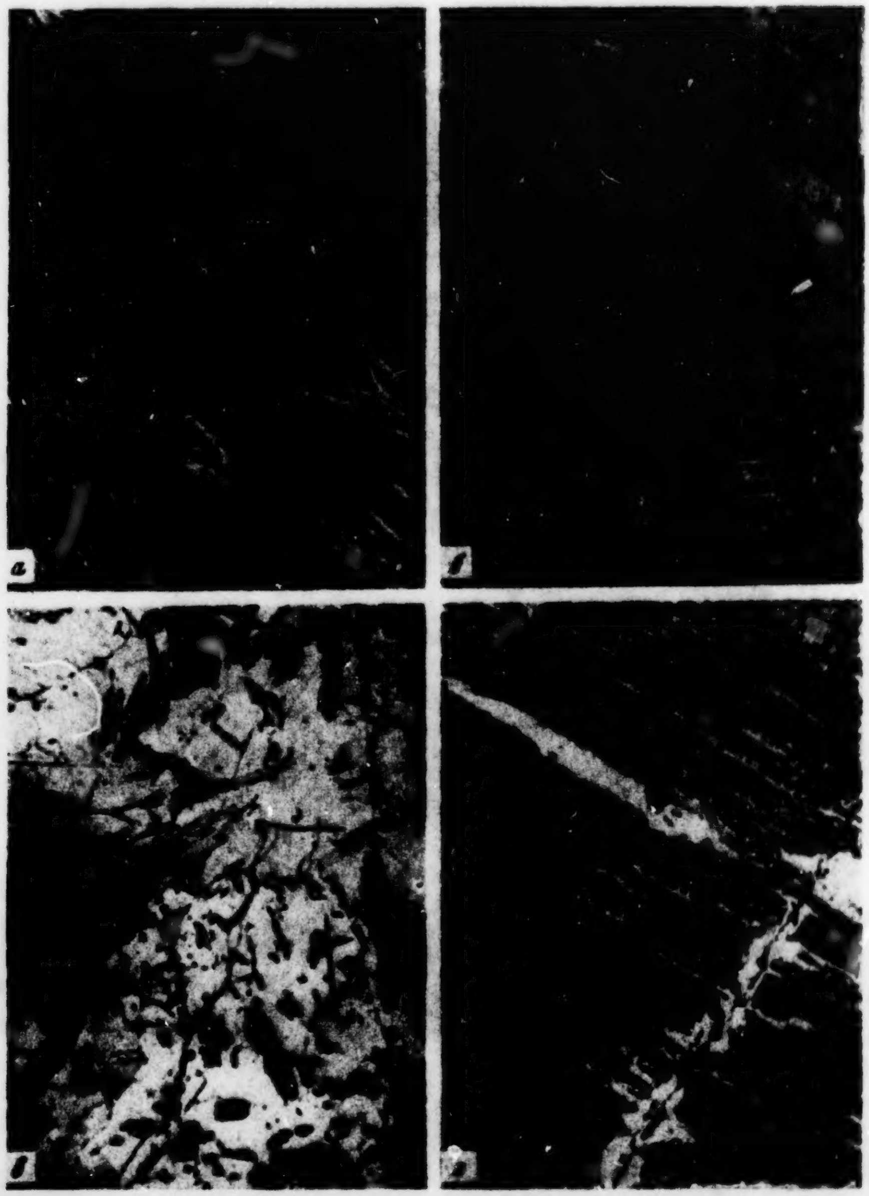
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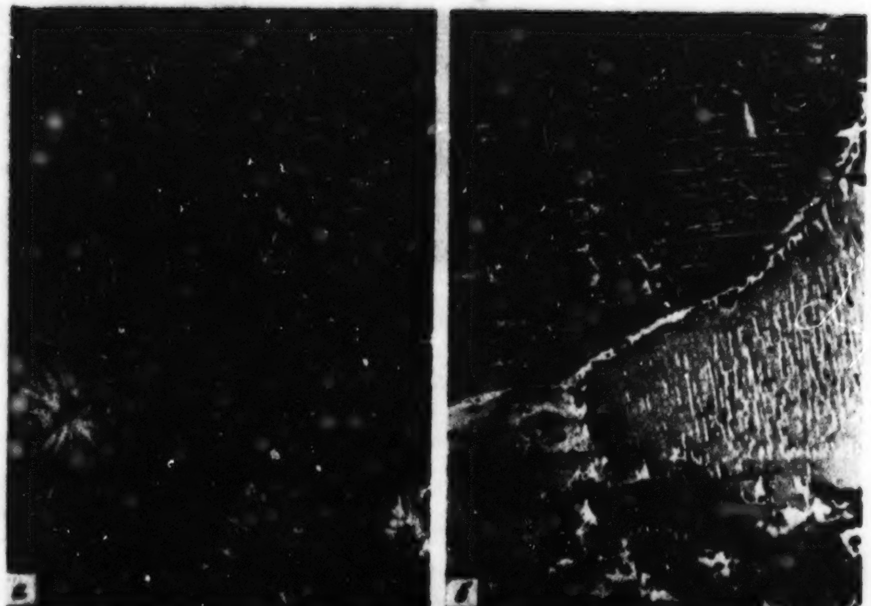
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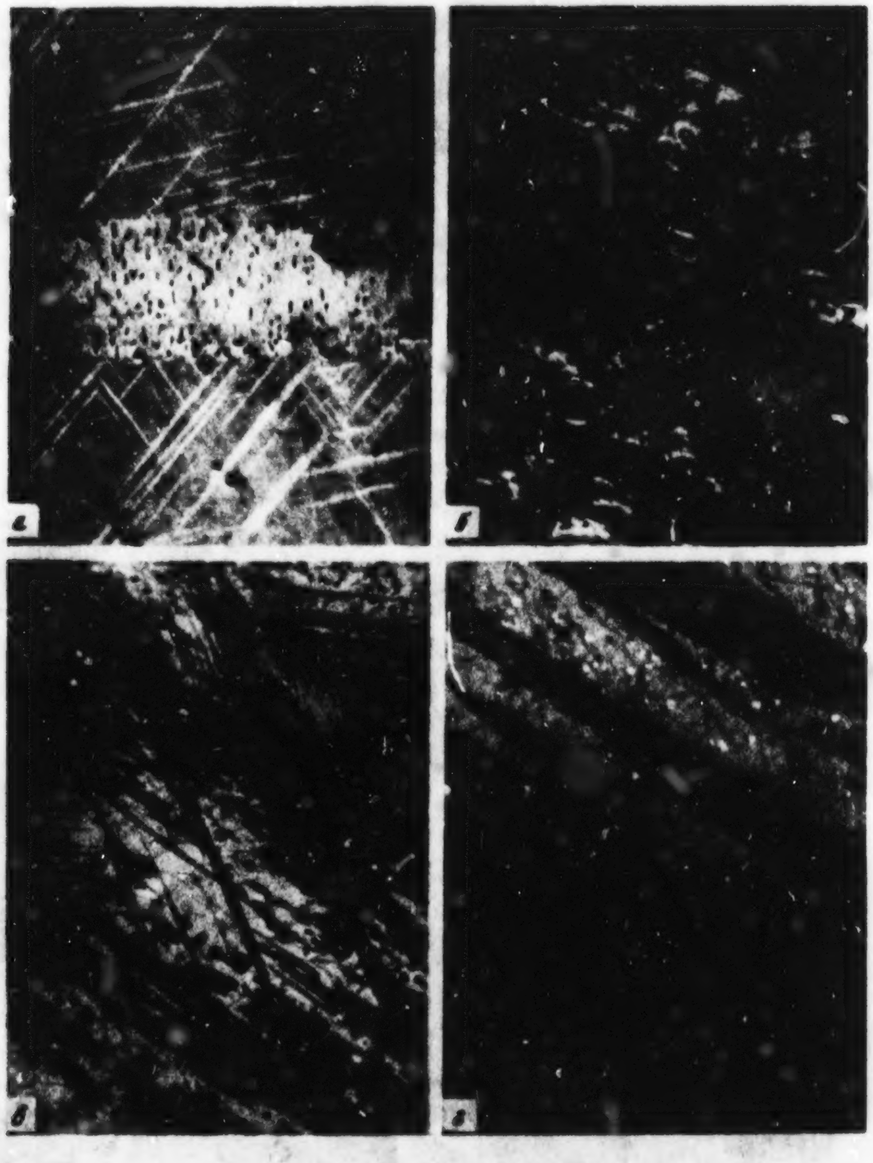
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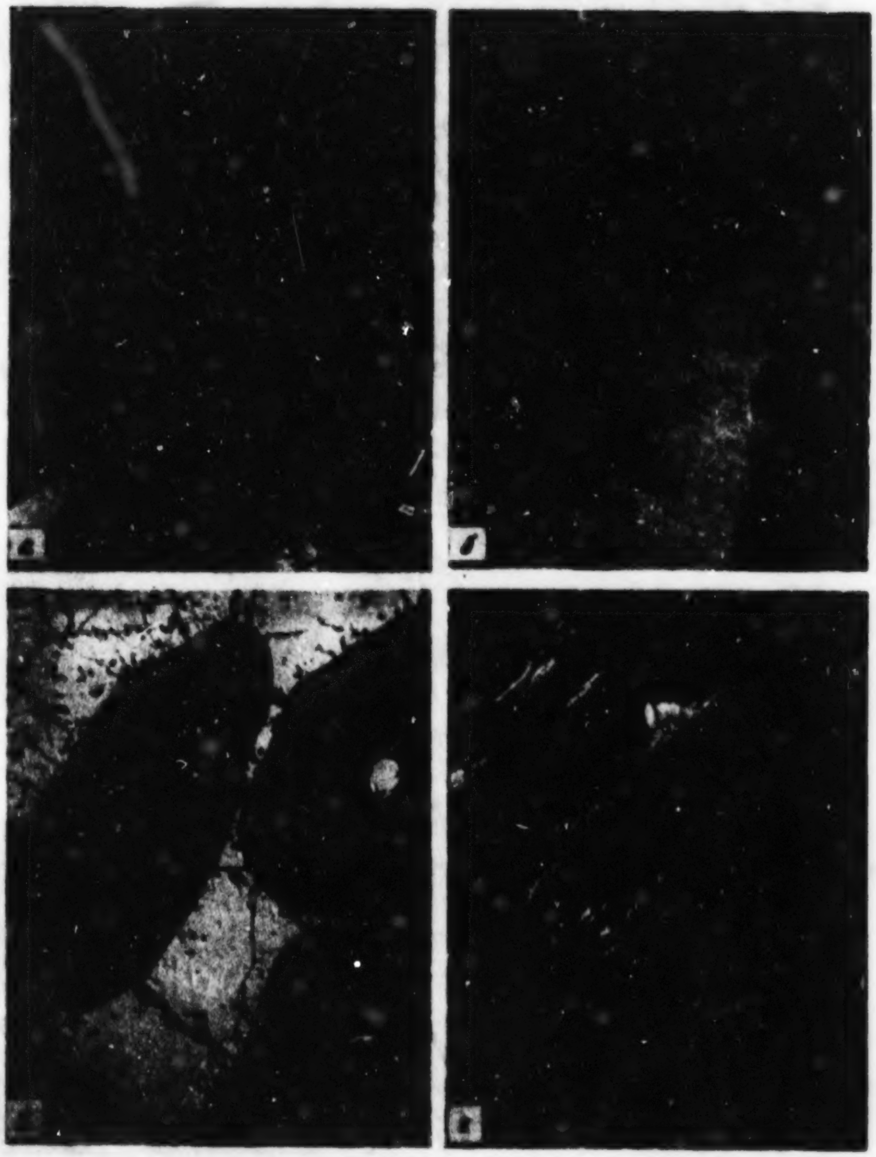
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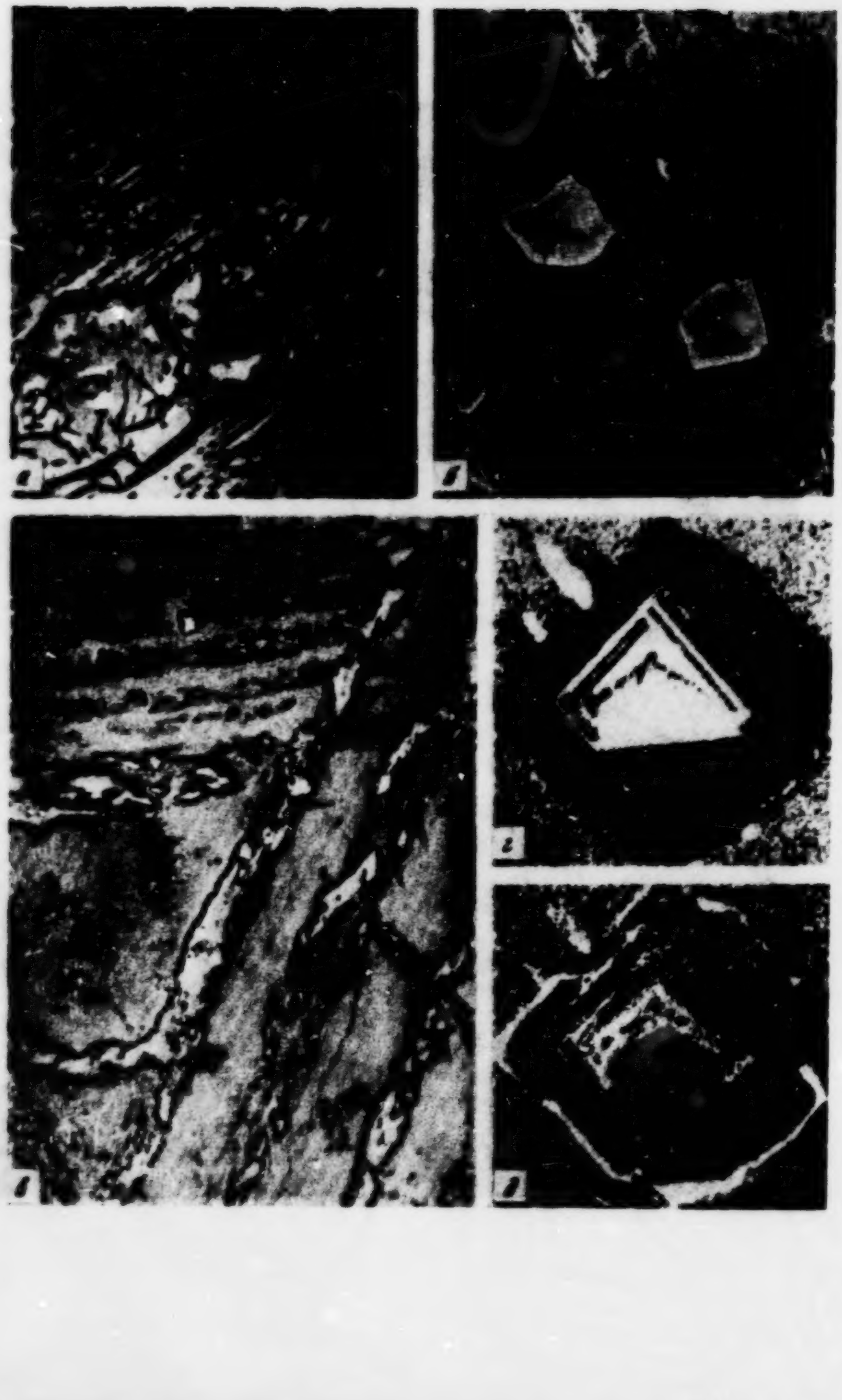
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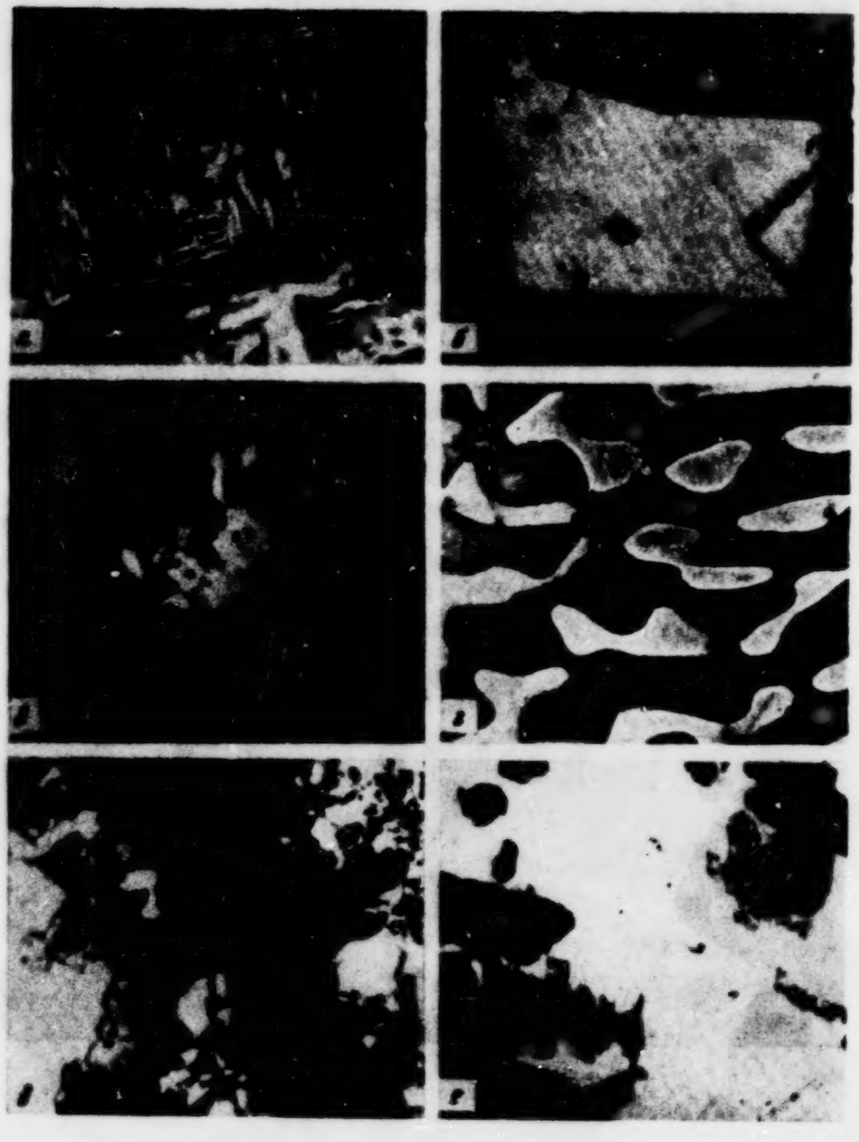
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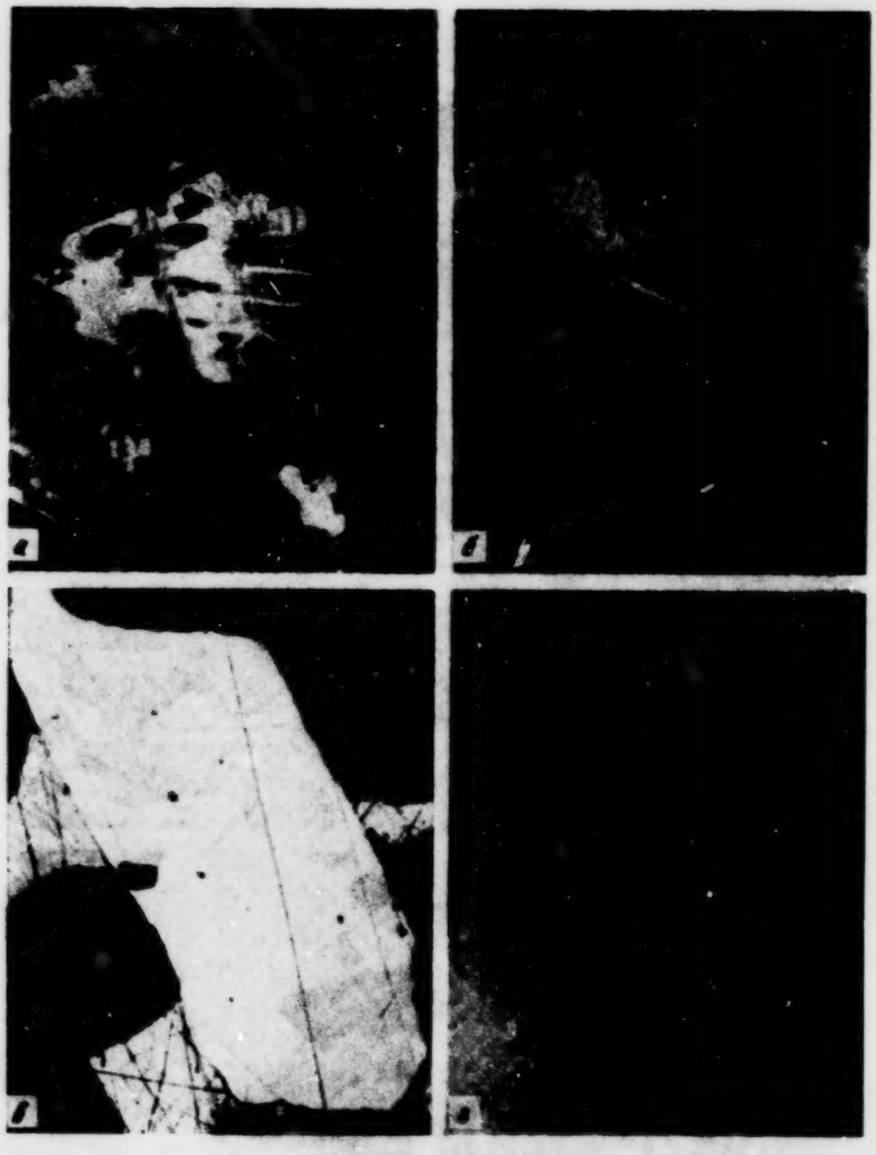
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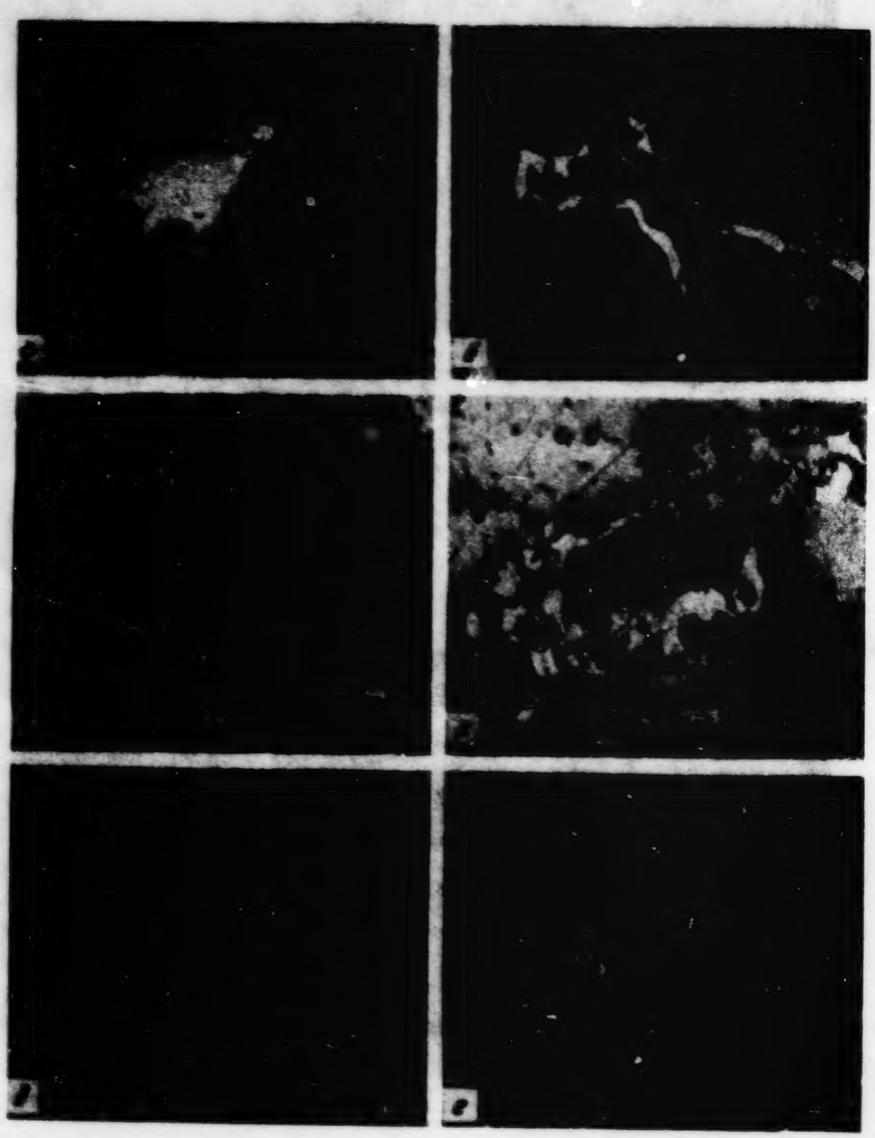

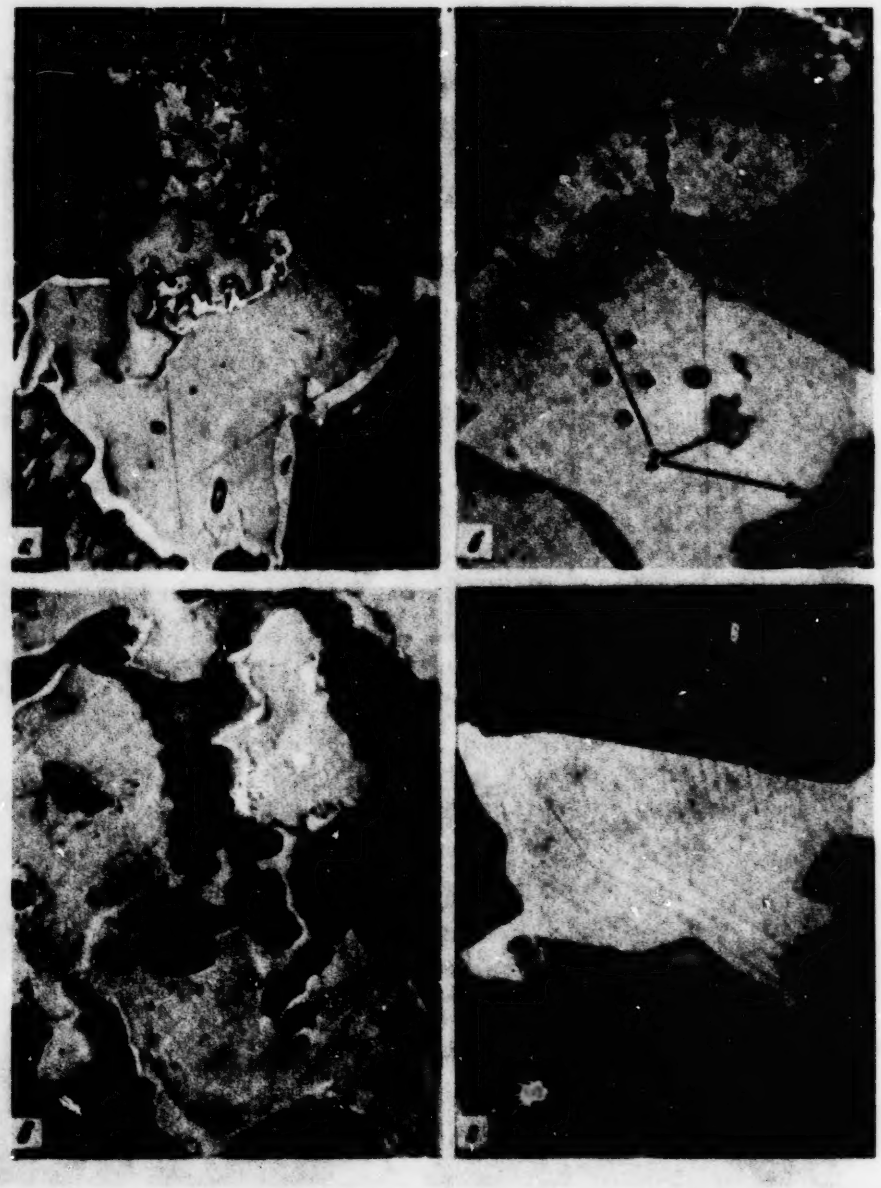

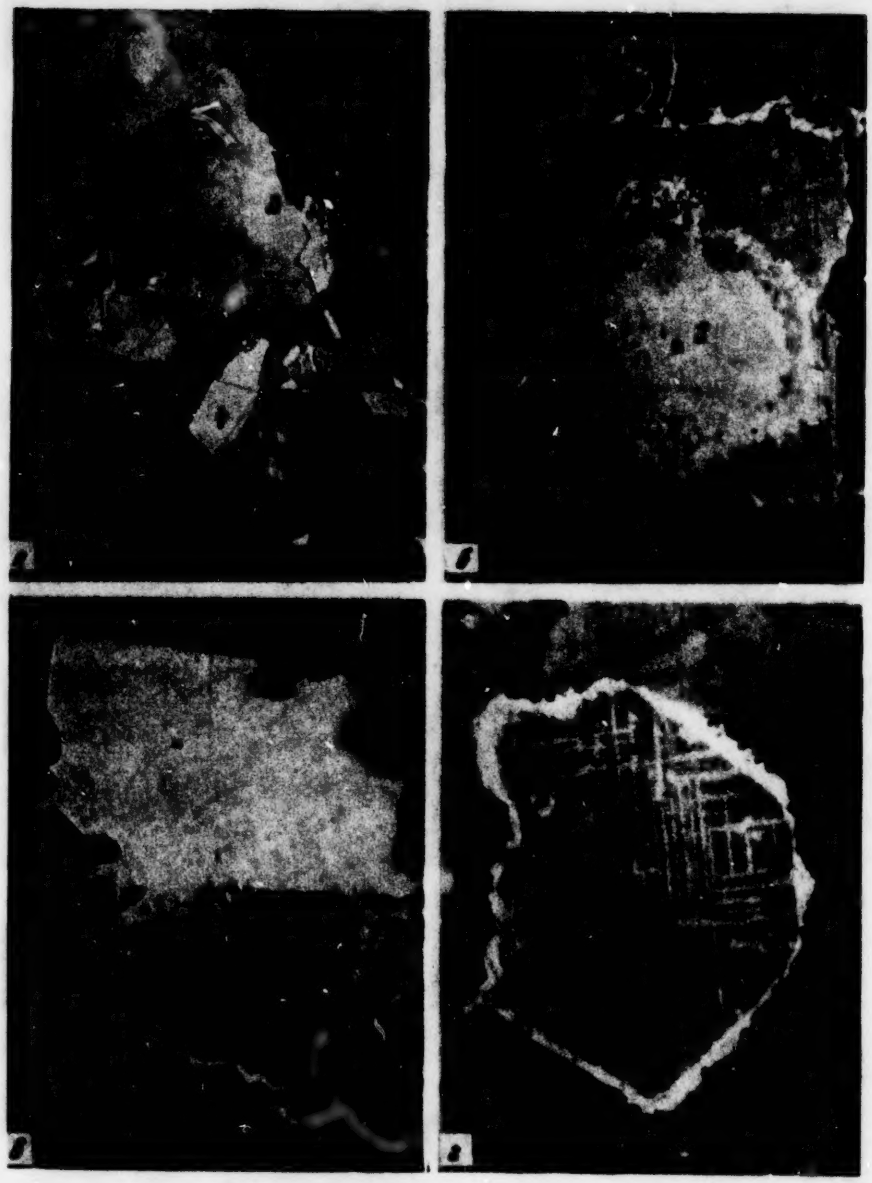
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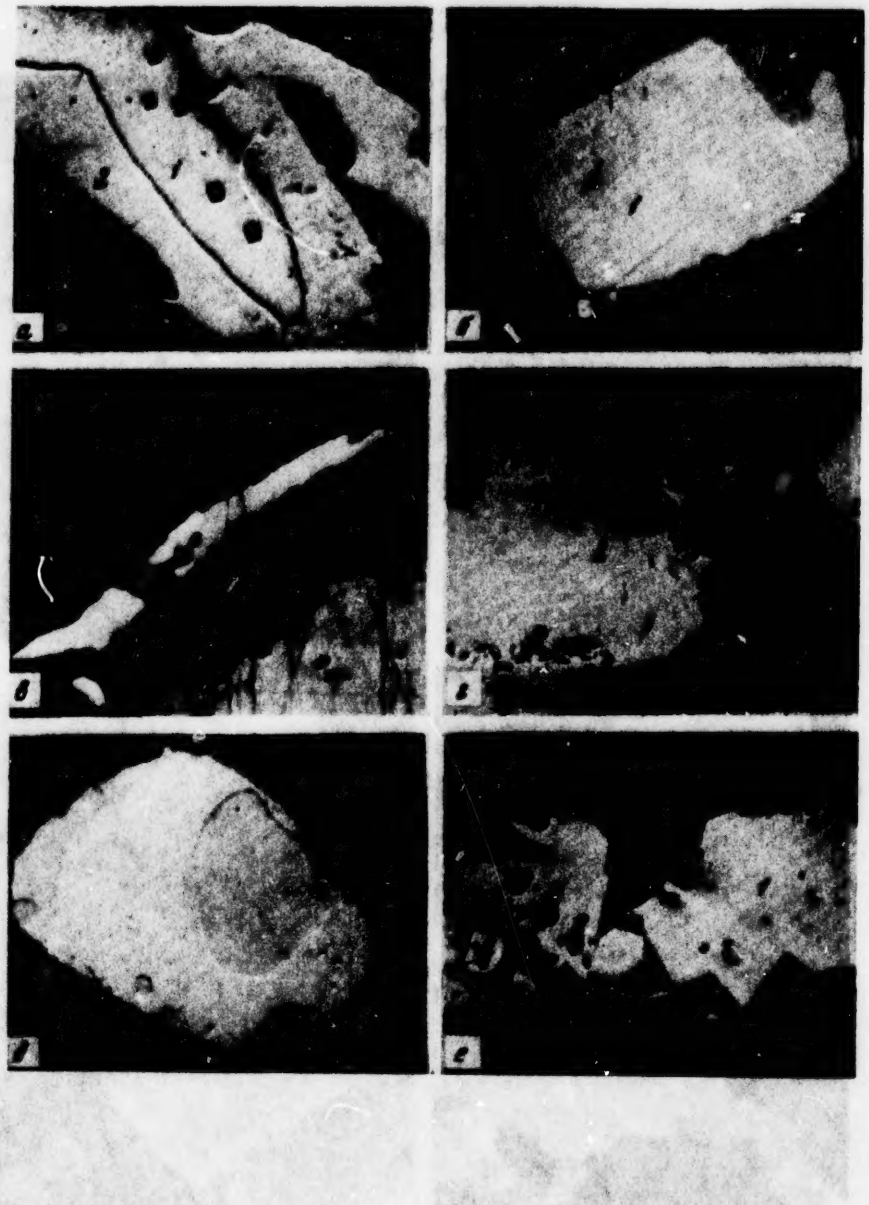
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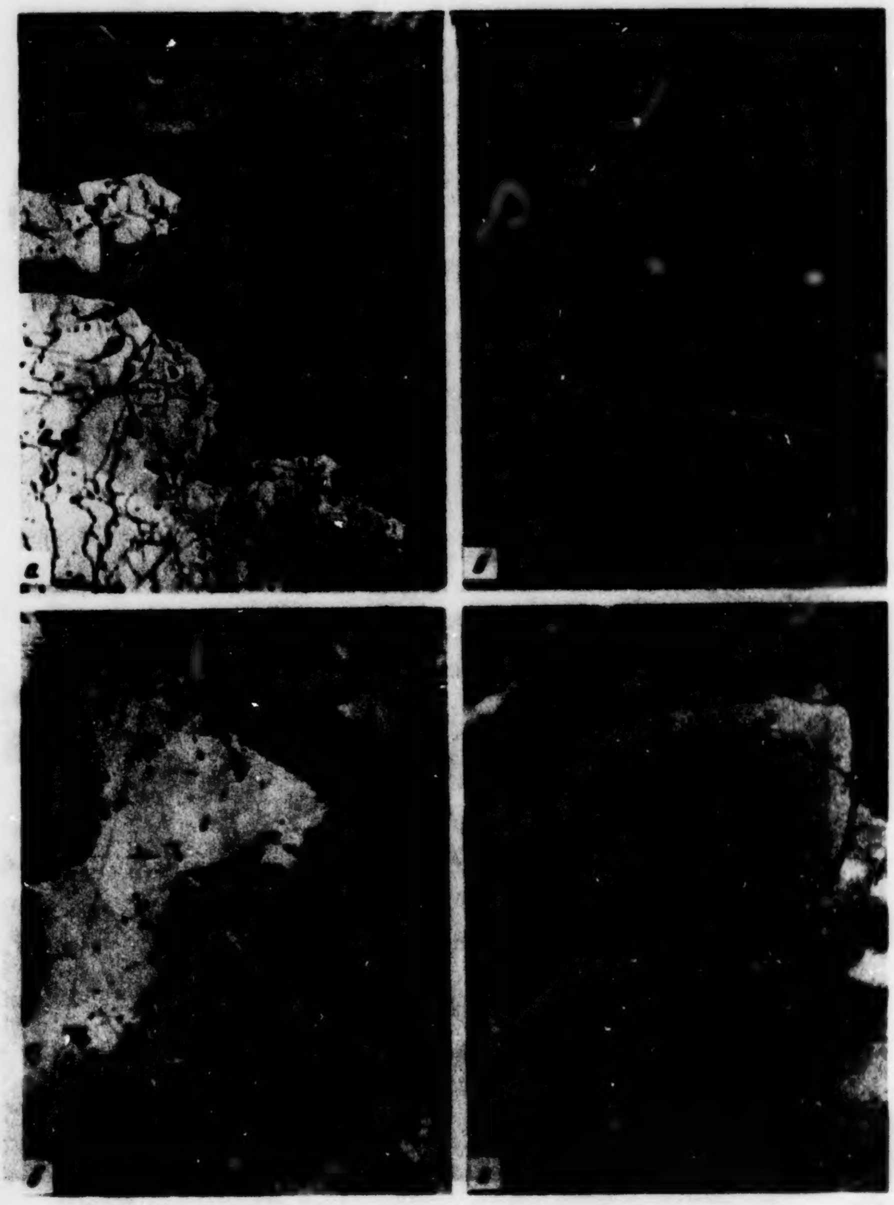

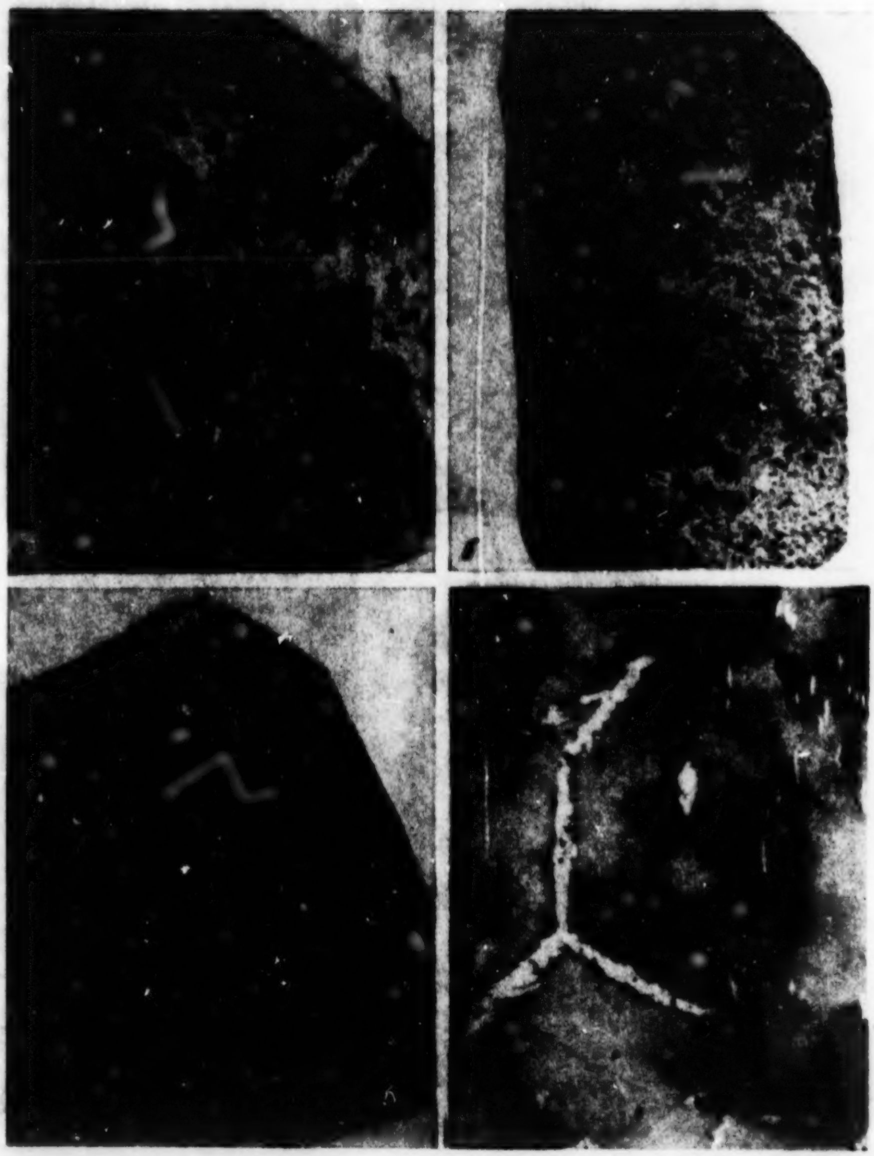

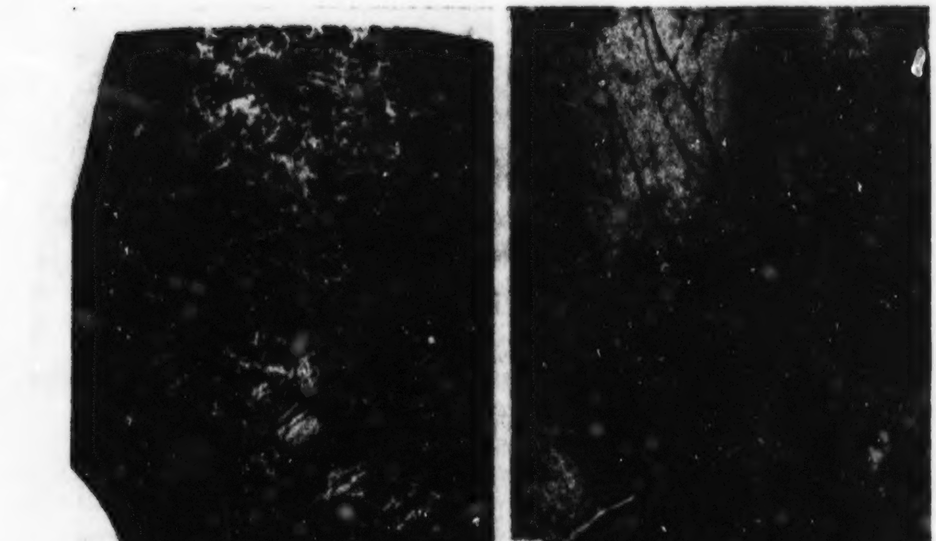

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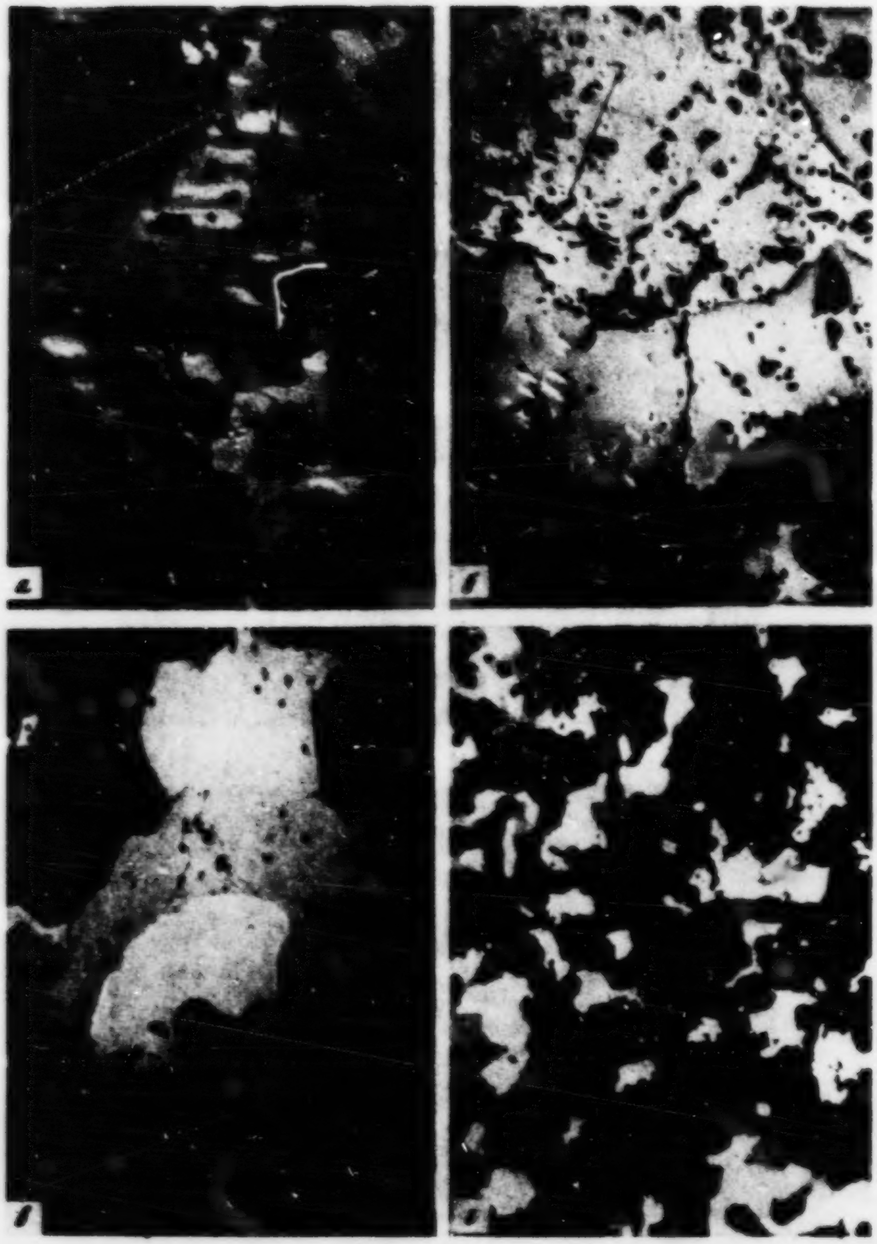
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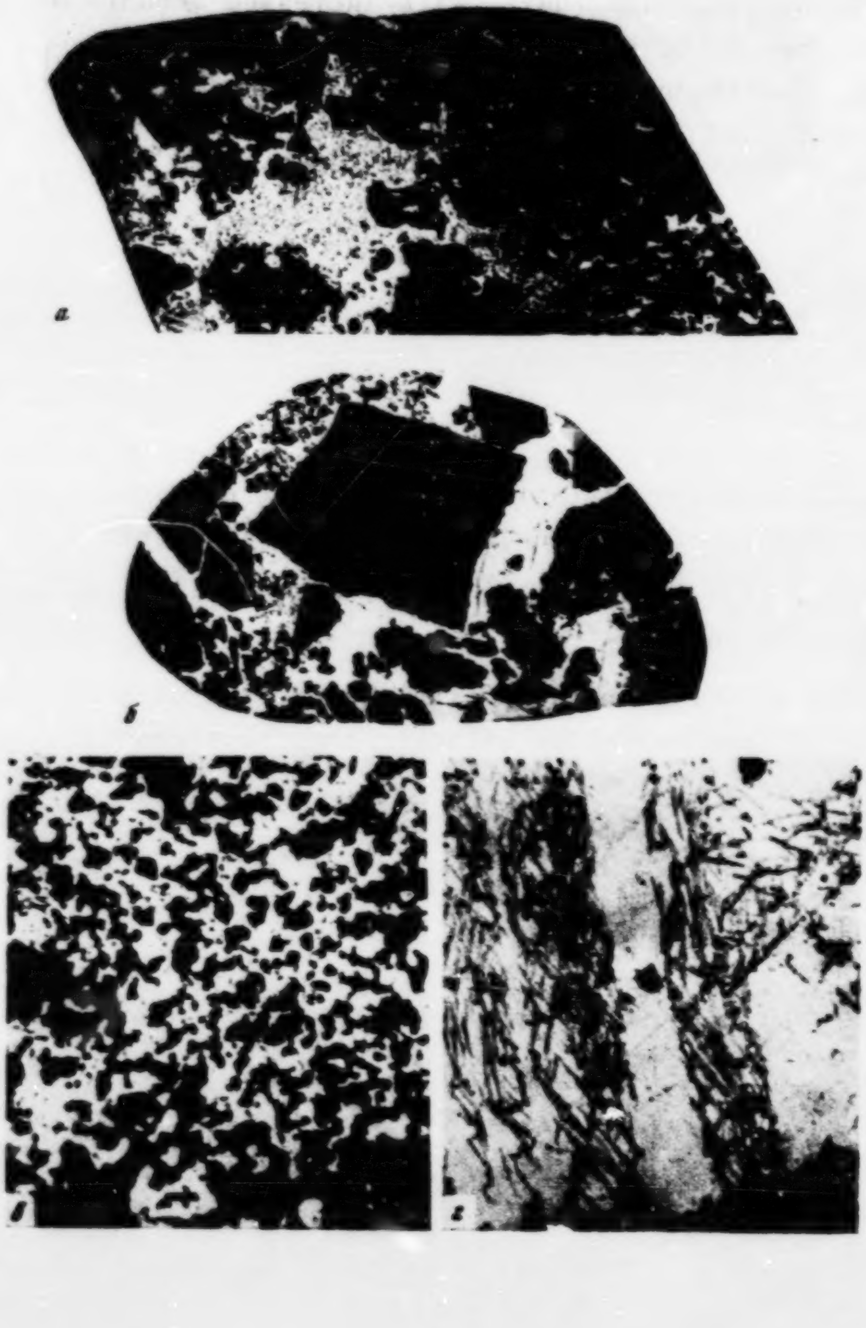
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PLATES I-XXIV

PLATE I

a-Fragments of contact gabbro-dolerites in a veinlet of massive sulphides; polished lump, 1/3 natural size;

b-Straight contacts of massive sulphide veins (light-coloured) in olivine gabbro-dolerite (dark) with increased amounts of magnetite at the contacts (grey); the vein cavity forms as a result of the gabbro-dolerites' being forced apart (indicated by arrows); polished lump, 3/4 natural size.
1/4 8 Sulphide ores

PLATE II

a-Drop-like particles of sulphides (black) in recrystallized pyroxene hornfels; thin section, X15, without analyser;

b-Spotted (maculose) structure inherited by sulphides replacing chlorite-feldspar hornfels (grey).

c-Remelted quartz-feldspar rocks with graphic textures at the contact with massive sulphides (black); thin section, X15, with analyser.

PLATE III

a-Idiomorphic case-shaped crystal of clinopyroxene (grey) in massive sulphide ore (black). See the composition of this clinopyroxene grain in Table 9, sample 9400-1, thin section, X15, without analyser;

b-Replacement of a Labrador basalt fragment (dark) by sulphides (light); primary morphology of the fragment becomes restored in the form of a close-grained sulphide-magnetite aggregate with relicts of a volcanic material; magnetite fringe observable around large relicts of basalts; polished lump, 2/3 natural size.

PLATE IV

a-Recrystallized idiomorphic grains of forsterite (grey) amidst sulphides (light-coloured); polished section, X20, without analyser;

b-Fringe of large-grained idiomorphic monticellite crystals (white) around a sulphide veinlet (grey), polished lump, 1/2 natural size.

PLATE V

a-Thin lamellas of troilite (grey) in hexagonal pyrrhotite (dark-grey); polished section, X90, without analyser;

b-Small loci of hexagonal pyrrhotite (light) in monoclinic pyrrhotite (dark) that also occurs in the form of thin lamellar or veinlet-like particles (agglomerations) in hexagonal pyrrhotite; polished section, X165, without analyser.

PLATE VI

a-Dendritic particles (agglomerations) of pentlandite (white) in sections of pyrrhotite parallel to (0001); polished section, X100, without analyser;

b-Lamellar crystals and flames of pentlandite (white) in variously oriented grains of pyrrhotite (grey); these particles are lacking near the pentlandite border inbetween the grains of pyrrhotite; the light-grey is chalcopyrite; polished section, X40, without analyser;

c-Borders of pentlandite (white) along the boundaries of pyrrhotite I (grey); polished section, X85, without analyser;

d-Porphyritic phenocrysts of pentlandite (white) amidst chalcopyrite (light-grey); polished section, X85, without analyser.

PLATE VII

a-Talnakhite (grey) enclosing thin, regularly oriented lamellas of tetragonal chalcopyrite (light-grey) and a larger tabular particle of cubanite (in the centre of the photograph); the small dark inclusions in cubanite are composed of valleriite; polished section, X320, without analyser;

b-Polysynthetically twinned grains of mooihoekite (various shades of grey) in intergrowths with close-grained aggregates of abnormally anisotropic cubic chalcopyrite (white and dark-grey); polished section, X70, with analyser;

c-Intergrowths of mooihoekite (dark-grey) and abnormally anisotropic cubic chalcopyrite (light-grey); polished section,X70, with analyser;

d-Lamellar intergrowths of cubic chalcopyrite (dark-grey) with abnormally anisotropic cubic chalcopyrite (light-grey). The white dot-like particles are mackinawite. Polished section, X90, with analyser.

PLATE VIII

a-Lamellas of cubanite I (light-grey) in tetragonal chalcopyrite (grey); in the lower right corner - granular cubanite II; polished section, X90, without analyser;

b-Veinlet-like agglomerations of granular cubanite II (light-grey) in talnakhite (grey); polished section, X90, without analyser;

c-Large grains of magnetite (grey) amidst pyrrhotite (light-grey) in massive pyrrhotite ores; polished section, X45, without analyser;

d-Lamellar particles of magnetite (thin dark-grey bands) amidst pyrrhotite; white - pentlandite; polished section, X160, without analyser.

PLATE IX

a-Finely intergrown pyrite (white) and lenticular inclusions of magnetite (black) developing in pyrrhotite, and a pseudomorph of polydymite (1) and millerite (2) in pentlandite; polished section, X160, without analyser, taken with immersion;

b-Zoned pyrite crystals amidst pyrrhotite (grey) containing inclusions of chalcopyrite (1), argentopentlandite (2) and pentlandite (3); polished section, X100, without analyser;

c-Pyrite (white) replacing lamellar particles of pyrrhotite (grey) in chalcopyrite (light-grey); polished section, X85, without analyser;

d-Scanning of a zoned pyrite crystal under an electron probe in characteristic X-ray radiation NiK_{a1};

e-Same in CoK_{a1} rays, X300.

PLATE X

a-Intergrowths of millerite (white), chalcopyrite (grey) and nickeloan pyrite (raised grains) developing in pentlandite; vysotskite grain (1) in the centre; millerite-chalcopyrite exocontact ores; polished section, X150, without analyser;

b-Idiomorphic crystals of polydymite (white) amidst bornite (dark-grey) and chalcopyrite (grey); stromeyerite and galena (2) intergrown with polydymite; veinlet-impregnated bornite-millerite-chalcopyrite ores; polished section; X320, without analyser;

c-Heazlewoodite (white) in a veinlet of chalcocite (grey) in bornite (dark-grey) containing minutest inclusions of pentlandite (white); polished section, X100, without analyser;

d-Subgraphic intergrowths of galena (white) and chalcopyrite (grey); massive chalcopyrite ores; polished section, X40, without analyser;

e-Veinlet of diaspore (dark-grey lamellar crystals), valleriite (1) and magnetite (2) in chalcopyrite (white); polished section, X85, without analyser;

f-Grains of argentopentlandite (dark-grey) in chalcopyrite (white) overgrowing pyroxene (black); polished section, X380, without analyser.

PLATE XI

a-Cuproan pentlandite (light-grey) and pentlandite (white) with a border of magnetite (dark-grey); cubanite (grey); polished section, X165, without analyser;

b-Twinned grains of godlevskite (grey and light-grey) amidst bornite (dark-grey); polished section, X90, with analyser;

c-Lamellar grains of hauchecornite (white) amidst galena (light-grey); black - nonmetalliferous minerals; veinlet-impregnated chalcocite-bornite ores; polished section, X200, without analyser;

d-Spherical and elongated particles of parkerite (light-grey) in galena (grey) amidst nonmetalliferous minerals (dark-grey); veinlet-impregnated chalcocite-bornite ores; polished section, X200, without analyser.

PLATE XII

a-Particles of djerfisherite (dark-grey) in association with platinum minerals (bright white); grey - cubanite; light grey - pentlandite; polished section, X165, without analyser;

b-Nickeloan djerfisherite forms a border around a pyrrhotite-chalcopyrite inset in the rock and is separated from pyrrhotite (grey) by a slender border of pentlandite (white); polished section, X85; without analyser;

c-Veinlet of Mn-shadlunite (grey) in cubanite (light-grey); polished section, X280, without analyser;

d-Alabandite (dark-grey) in cubanite (light-grey) with a border of pentlandite (white); polished section, X165, without analyser;

e-Lamellar grain of thalcusite (dark-grey) in chalcopyrite (grey); light grey-galena; massive chalcopyrite ores; polished section, X540, without analyser; photographed with immersion;

f-Regular intergrowths of altaite (white) and galena (grey); massive chalcopyrite ores; polished section, X320, without analyser.

PLATE XIII

a-Intergrowths of nickeline (grey) and diarsenides of iron, nickel and cobalt (light-coloured); polished section, X90, without analyser;

b-Stellular aggregates of diarsenide crystals (white) in calcite (black); polished section, X90, without analyser;

c-Diarsenides (white) forming a border around native arsenic (light-grey) and stellular crystals in native arsenic; black - calcite; polished section, X45, without analyser;

d-Intergrowths of diarsenides (light-coloured) and tetrahedrite (dark-grey) in calcite (black); polished section, X90, without analyser;

e-g---Microheterogeneity of diarsenide crystals; scanning under the electron probe in characteristic X-ray radiation (e-NiK_{a1}; f-CoK_{a1}; and g-SK_{a1}); X400.

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PLATE XIV

a-Perovskite crystals (grey) with minutest cribriform inclusions of silicates amidst insets of chalcopyrite (white) in altered rock; polished section, X200, without analyser;
b-Electrum (white) replacing bornite (dark-grey) and chalcocite (grey) amidst nonmetalliferous minerals (black); veinlet-impregnated chalcocite-bornite ores; polished section, X40, without analyser;
c-Veinlet of native silver (white) amidst talnakhite (grey) and cubanite (light-grey); massive cubanite-mooihoekite ores; polished section, X780, without analyser;
d-Intergrowths of hessite (grey) with tellurian sobolevskite (white); veinlet-impregnated chalcocite-bornite ores; polished section, X40, without analyser.

PLATE XV

a-Ferroplatinum (1) border around stannopalladinite (2) overgrown by polarite (3); polished section, X90, without analyser;
b-Particles of palladian rustenburgite (1),$Pd_2(As,An)$ (2); plumbopalladinite (3) and native silver (4) amidst talnakhite (dark-grey); polished section, X165, without analyser;
c-Grains of stannoan zvyangintsevite (light-grey) with a border of ferroplatinum (white) amidst pentlandite (grey); polished section, X160, without analyser;
d-Paolovite (white) with polysynthetically twinned grains overgrowing magnetite (black); grey - cubanite, light grey - talnakhite; polished section, X180, without analyser.

PLATE XVI

a-Mineral $(Pd, Pt)_5(Sn, As, Sb)_2$ (1) intergrown with sperrylite (2), polarite (3) and ferroplatinum (4) amidst pentlandite (5); polished section, X180, without analyser;
b-Intergrowth of stennopalladinite (1), platinian atokite (2) and ferroplatinum (3) amidst cubanite and pentlandite; polished section, X90, without analyser;
c-Mineral $Pd_2(Sn, Cu)$ (light-grey) intergrown with sperrylite (white); dark grey - bornite, black - silicates; polished section, X165, without analyser;
d-Intergrowth of plumbopalladinite (grey) and polarite (light-grey); white border - native silver, dark-coloured area - talnakhite; polished section, X165, without analyser.

PLATE XVII

a-Intergrowth of sobolevskite (1) and paolovite (2); grey area - chalcopyrite; polished section, X165, without analyser;
b-Telargpalite (2) replacing kotulskite (1); dark-grey area - chalcopyrite, black - nonmetalliferous minerals; polished section, X560, without analyser; photographed in immersion;
c-Microveinlet of michenerite (light-grey) and merenskyite (white) confined to fine-grained pyrrhotite II (dark-grey) in chalcopyrite (grey); polished section, X320, without analyser;
d-Intergrowth of minerals Pd_3As_2(1), $(Pd,Ni)_5As_2$ (2) and $Pd_2(As,Sn)$ (3) amidst pyrrhotite (4) and chalcopyrite (5); polished section, X180, without analyser;
e-Majakite (light-grey) in polarite (white); dark-grey area-chalcopyrite; section, X320, without analyser;
f-Sperrylite (1), $(Pd,Pb)_3As$ (2), ruthenian hollingworthite (4); dark-grey area - chalcopyrite; polished section, X160, without analyser.

PLATE XVIII

a-Large flattened-out phenocrysts and small interstitial insets of sulphides in picrite gabbro-dolerite; polished lump, natural size;
b-Xenomorphic insets of sulphides in taxite gabbro-dolerite; polished lump, X3;
c-Sulphide impregnation in interstices of olivine grains in picrite gabbro-dolerite; polished section, X40, without analyser;
d-Sideronitic impregnation of sulphides in equigranular olivine-containing gabbro-dolerite; silicate minerals are represented by idiomorphic grains of plagioclase and clinopyroxene; polished section, X40, without analyser.

PLATE XIX

a-Pentlandite-chalcopyrite-pyrrhotite ores in picrite gabbro-dolerites; porphyroid and lamellar particles of pentlandite (white); polished section, X40, without analyser;
b-Pentlandite-chalcopyrite-pyrrhotite ores in picrite gabbro-dolerites; intergrowth of small-grained pyrrhotite II (grey) and pentlandite (white) in chalcopyrite (light-grey); polished section, X90, without analyser;
c-Agglomeration of granular and platy (lamellar) cubanite (light-grey) in chalcopyrite (grey); dark-grey area-grains of magnetite; polished section, X70, without analyser;
d-Polysynthetic twinning of cubic chalcopyrite; polished section, X320, with analyser.

PLATE XX

a-Large-grained pyrrhotite ore; grey - pyrrhotite, light grey - chalcopyrite; the thin lamellar and punctulate inclusions in pyrrhotite are composed of pentlandite; the black punctulate particles are magnetite; polished lump, X2;
b-Small-grained pyrrhotite ore; light grey - sulphides, black - nonmetalliferous inclusions; polished lump, natural size;
c-Inequigranular pyrrhotite ore; large grains of pyrrhotite (grey) amidst an aggregate of smaller pyrrhotite grains intergrown with magnetite (black); polished lump, natural size;
d-Spherical grains of magnetite (black) amidst pyrrhotite crystals (grey); white - pentlandite; polished section, X40, without analyser.

PLATE XXI

a-Cubanite-talnakhite ore; dark spots - particles of pentlandite, grey - talnakhite, light grey - cubanite; polished lump, natural size;
b-Chalcopyrite ore; dark-grey - pentlandite, grey - chalcopyrite; polished lump, natural size;
c-Cubanite ore; grey - cubanite, black - magnetite; polished lump, natural size;
d-Relict agglomerations of troilite (dark-grey) in cubanite (grey); white - pentlandite; polished section, X70, without analyser.

PLATE XXII

a-Bornite-millerite-chalcopyrite ore with banded structure; white veinlet-anhydrite; polished lump, 3/4 natural size;
b-Disseminated insets and slender veinlets of sulphides in serpentine-hydrogarnet rock; polished lump, natural size;
c-Densely impregnated pyrrhotite ore in brucite rock; polished lump, natural size.

PLATE XXIII

a-Impregnated particles of pyrrhotite (grey) with inclusions of pentlandite flames (white) amidst pyroxene; polished section, X165, without analyser;

b-Borders of pentlandite (white) at the boundary of pyrrhotite (grey) and chalcopyrite (light grey); polished section, X85, without analyser;

c-Millerite (white), chalcopyrite (light-grey) and vysotskite (grey, raised) amidst pyroxene (black); polished section, X160, without analyser;

d-Fine intergrowths of bornite (dark-grey), millerite (white) and chalcopyrite (grey) amidst pyroxene (black); polished section, X160, without analyser.

PLATE XXIV

a-Brecciated structure of pyrrhotite ore; polished lump, natural size;

b-Brecciated structure of chalcopyrite ore; polished lump, natural size;

c-Densely impregnated chalcopyrite ore; sulphides cementing grains of pyroxenes; polished section, X40, without analyser;

d-Thin lamellar particles of pyrrhotite (grey) in chalcopyrite (light-grey) grouped into elongated parallel bands; polished section, X85, without analyser.

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* Breccioid = brecciated. Translator.

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COPPER-NICKEL SULPHIDE ORES
OF THE NORIL'SK DEPOSITS

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DIAGNOSTIKA I DIAGNOSTICHESKIE SVOISTVA MINERALOV // DIAGNOSTICS AND DIAGNOSTIC PROPERTIES OF MINERALS

The symposium covers studies on diagnostic properties of minerals and on the development of diagnostic techniques. Attention focuses to a significant degree on a new trend in automation of mineral diagnostics. Problems related to the classification of minerals and to the organization of diagnostic and information systems, and results from testing of algorithms and programs for automatic diagnostics of minerals are examined. Results from studies of optical, magnetic and other properties of minerals and their applicability in mineral diagnostics are outlined.

This work is intended for use by geologists, mineralogists and geochemists.

Vladykin N.V., Kovalenko V.I., Dorfman M.D.

MINERALOGICHESKIE I GEOKHIMICHESKIE OSOBENNOSTI KHAN-BOGDINSKOGO MASSIVE SHCHELOCHNYKH GRANITOV // MINERALOGICAL AND GEOCHEMICAL CHARACTERISTICS OF THE KHAN-BOGDINSKII* MASSIF OF ALKALI GRANITES

Geological and geochemical characteristics and mineralogy of the Khan-Bogdinskii massif of alkali granites in the People's Republic of Mongolia are described for the first time. The rocks of that massif have a unique mineralogy because of their high alkalinity and high content of zirconium, hafnium, rare-earth elements, etc. Over sixty minerals are examined in the work. Results of a large number of analyses are presented.

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* Transliteration. Translator.

The work is intended for mineralogists, geochemists and prospecting geologists.

Back cover:

COPPER-NICKEL SULPHIDE ORES OF THE NORIL'SK DEPOSITS

Copper-nickel sulphide deposits are of great interest not only on account of their economic importance, but also because they provide a great deal of information on magmatic ore formation. Studies of the Noril'sk deposits allowed us to determine the relations of sulphides and silicates in the processes of plutonic magmatic differentiation and crystallization of melts under hypabyssal conditions; patterns of crystallization of paragenetic sequences of magmatic sulphides; causes and conditions of formation of ores that are unique on account of their highly diversified mineral composition; and factors responsible for the formation of mineral zoning in ore bodies and deposits.

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